Sedimentology, Conodonts, Structure, and Regional Correlation of Silurian and Devonian Metasedimentary Rocks in Denali National Park, Alaska

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ABSTRACT

A sequence of metasedimentary rocks in Denali National Park (Mt. McKinley and Healy quadrangles), previously mapped by Csejtey and others (1992) as unit DOs (Ordovician to Middle Devonian metasedimentary sequence) and correlated with rocks of the Nixon Fork terrane, contains both deep- and shallow-water facies that correlate best with rocks of the Dillinger and Mystic sequences (Farewell terrane), respectively, exposed to the southwest in the McGrath quadrangle and adjacent areas.

New conodont collections indicate that the deep-water facies are at least in part of Silurian age, and can be grouped into three broad subunits. Subunit A is chiefly very fine grained, thinly interbedded calcareous, siliceous, and siliciclastic strata formed mostly as hemipelagic deposits. Subunit B is characterized by abundant calcareous siliciclastic turbidites and may correlate with the Terra Cotta Mountains Sandstone in the McGrath quadrangle. Subunit C contains thin-bedded to massive calcareous turbidites and debris flows, locally intercalated with calcareous siliciclastic turbidites. Sedimentary features suggest that subunits B and C accumulated in a fan and (or) slope apron setting. All three subunits contain subordinate layers of altered tuff and tuffaceous sediment. Turbidites were derived chiefly from a quartz-rich continent or continental fragment and a carbonate platform or shelf, with subordinate input from volcanic and (possibly) subduction complex (accretionary prism) sources. Limited paleocurrent data from subunit B turbidites show generally southward transport. Stratigraphic relations between the three subunits are uncertain, although we believe that subunit A is probably the oldest. Shallow-water facies, at least in part of earliest Late Devonian (early Frasnian) age, are exposed locally and were deposited in intertidal to deeper subtidal settings.

Reconnaissance structural studies indicate that the most significant of two generations of folds have northerly vergence and presumably are the product of Mesozoic plate convergence.

Deep-water rocks of Silurian age have been recognized in six Alaskan terranes outside the Farewell terrane. Comparison of unit DOs with coeval strata in these terranes reveals closest sedimentologic and biostratigraphic similarities with rocks of east-central Alaska (Livengood terrane) and western Alaska (Seward terrane) and less striking similarities with rocks in southeastern Alaska (Alexander terrane) and northern Alaska (Hammond subterrane of Arctic Alaska terrane). Coeval sequences in easternmost Alaska (Porcupine and Tatonduk terranes) correlate least well with DOs because they lack both Silurian siliciclastic turbidites and Upper Devonian platform carbonate rocks. Our correlations permit the interpretation that all Alaskan terranes with Silurian deep-water strata originated along or adjacent to the North American continental margin, but imply a gradient in Silurian turbidite distribution along this margin. Volcanic material preserved in DOs and related rocks may have been derived from the island arc represented by the Alexander terrane.

INTRODUCTION

Lower and middle Paleozoic metasedimentary rocks (unit DOs, Ordovician to Middle Devonian metasedimentary sequence, of Csejtey and others, 1992) form an east-trending belt on the north side of the Denali fault in Denali National Park (Mt. McKinley and Healy quadrangles; figs. 1, 2). These rocks have been variously correlated (Jones and others, 1981, 1982, 1983; Mullen and Csejtey, 1986; Csejtey and others, 1992, 1996) with different parts of the Farewell terrane (Decker and others, 1994) but have received little detailed investigation. We report here the results of a reconnaissance study of the lithofacies, conodont age and biofacies, and structure of DOs in the Mt. McKinley B-1 and Healy B-6 quadrangles, and evaluate possible correlations between DOs and coeval sequences in the Farewell terrane and elsewhere in Alaska. Lower Paleozoic strata throughout Alaska are poorly understood and are considered by many authors to belong to numerous discrete tectonostratigraphic terranes (Jones and others, 1981; Silberling and others, 1994). Most of these terranes are interpreted as displaced pieces of the continental margin of North America, but some may represent fragments of other continental margins (for example, Siberia) or of island arcs (Nokleberg and others, 1994; Soja, in press). Detailed comparisons of Paleozoic rocks throughout Alaska are essential in understanding the ultimate origin of these terranes.

GEOLOGIC SETTING

The Farewell terrane of Decker and others (1994) incorporates three previously defined units: (1) the Nixon Fork terrane (Patton, 1978); (2) the Dillinger terrane (Jones and others, 1981) or sequence (Gilbert and Bundtzen, 1984); and the Mystic terrane (Jones and others, 1981) or sequence (Gilbert and Bundtzen, 1984). Different authors have proposed various definitions and boundaries for these three units and have disagreed on whether or not they are genetically related to each other and to the North American craton (compare Decker and others, 1994; Patton and others, 1994; Silberling and others, 1994). Most workers, however, favor a North American origin for these units (Decker and others, 1994; Nokleberg and others, 1994).

We follow here most of the conventions and interpretations outlined by Decker and others (1994). These authors (p. 288) interpreted the Farewell terrane as a coherent, but locally highly deformed, continental margin succession made up of the Middle Cambrian through Middle Devonian White Mountain sequence and the overlying Upper Devonian through Lower Cretaceous Mystic sequence. The contact between the two sequences is generally an angular unconformity, but it is locally conformable. The White Mountain sequence includes both platform and deeper water (slope and basinal) facies, called Nixon Fork and Dillinger terranes (or sequences), respectively, by previous authors. We agree with Decker and others (1994) that these two assemblages probably formed as part of a single continental margin succession, but we retain the term "Dillinger sequence" for convenience.

Rocks of the DOs unit, initially described as part of the Dillinger terrane by Jones and others (1981), are complexly folded and faulted and have been subjected to low-grade regional metamorphism; they contain conodonts with color alteration indices of 5 to 5.5, indicating that the host rocks reached temperatures of at least 300 to 350°C (Epstein and others, 1977). Parts of DOs in our study area retain little original fabric; some carbonate intervals are pervasively recrystallized, and some siliciclastic layers are slightly to strongly semischistose. Other parts of DOs, however, particularly sections which are thick-bedded and (or) dolomitic, have well-preserved primary sedimentary textures.

As mapped by Csejtey and others (1992) and Jones and others (1983), the outcrop belt of DOs is bounded on the south by the Denali strike-slip fault, beyond which are rocks unrelated to DOs: the Windy terrane (melange), and a belt of

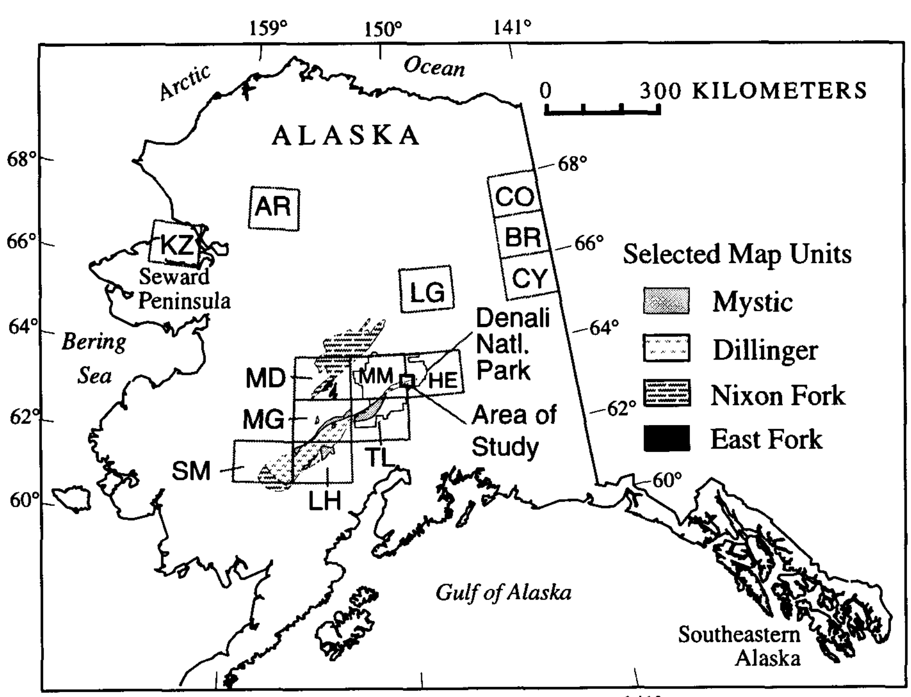

Figure 1. Location of quadrangles and selected tectonostratigraphic terranes mentioned in text; East Fork is East Fork subterrane of Minchumina terrane (Patton and others, 1994). Terranes from Silberling and others (1994), modified in the McGrath and Medfra quadrangles based on Decker and others (1994). Quadrangles: AR, Ambler River; BR, Black River; CO, Coleen; CY, Charley River; HE, Healy; LG, Livengood; LH, Lime Hills; KZ, Kotzebue; MD, Medfra; MG, McGrath; MM, Mt. McKinley; SM, Sleetmute; TL, Talkeetna.

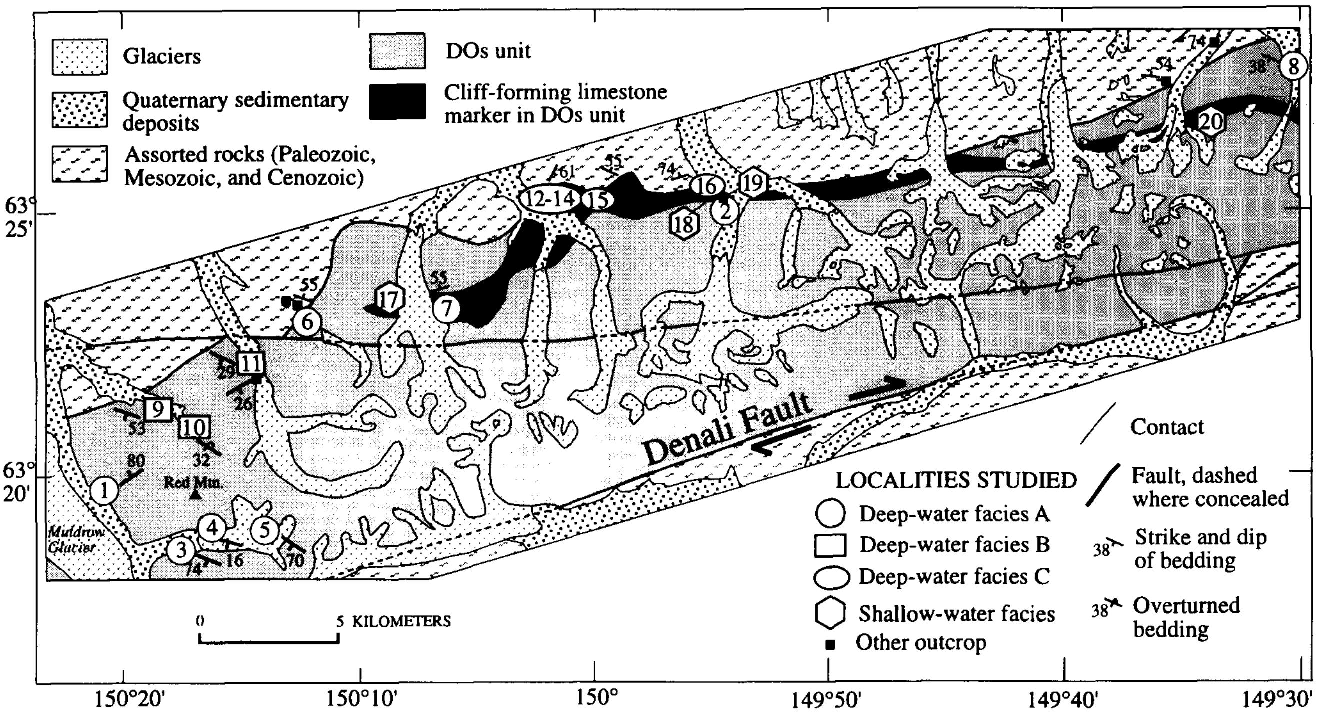

Figure 2. Location of lithologic and fossil collections and structural data from study area in Denali National Park (Healy and Mt. McKinley quadrangles). "Other outcrop" symbol within DOs map pattern indicates rocks assigned to DOs but not assigned to a facies or subunit; elsewhere, symbol indicates rocks other than DOs.

Jurassic-Cretaceous flysch (Kahiltna terrane). According to Csejtey and others (1992), DOs is bounded on the north by an unnamed fault (fig. 2), which they interpreted as a north-directed thrust fault. At various places along the footwall are Upper Triassic to Pennsylvanian flysch; Upper Triassic basalt, diabase, and sedimentary rocks; Lower Cretaceous and Upper Jurassic flysch; and the Upper Cretaceous (Ridgway and others, 1997) sedimentary member of the Cantwell Formation. Ridgway and others (1997) have shown that sediments that formed the Cantwell were shed northward from active thrusts in the ancestral Alaska Range. Fluvial conglomerates in the Cantwell include abundant limestone clasts that Csejtey and others (1992, 1996) traced to unit DOs.

PREVIOUS WORK AND METHODS

Lower and middle Paleozoic metasedimentary rocks in the study area were first described by Jones and others (1981, 1982, 1983; unit "Pzd") as "turbidites and basinal facies" (Jones and others, 1982, p. 3712). These publications included brief lithologic summaries and mentioned a single fossil collection, gastropods of Middle Ordovician to Devonian age, from the easternmost part of the unit in the Healy B-5 quadrangle. Mullen and Csejtey (1986) and Csejtey and others (1992) mapped these rocks as unit "DOs" in the Healy quadrangle, supplied additional descriptions of the deep-water facies, recognized and briefly described shallow-water facies in the unit, and reported a few additional fossil localities. Constraints on the age of DOs were provided chiefly by conodont collections (Csejtey and others, 1992) from carbonate pebbles in nearby exposures of the Upper Cretaceous sedimentary part of the Cantwell Formation; these pebbles were interpreted as derived from DOs. Refinements of faunal ages for these cobbles, as well as new megafossil and conodont data from a single locality of Frasnian (early Late Devonian) age in the shallow-water facies of DOs (fig. 2, loc. 19), were given by Csejtey and others (1996). Savage and others (1995) reported additional faunal and lithologic details for locality 19.

We examined the DOs unit at 20 localities in the study area (fig. 2) and measured sections at five good exposures. Sedimentologic and petrographic descriptions are based on field observations and examination of 125 thin sections. Shallow-water carbonate rocks in which primary texture can be recognized are classified after Dunham (1962). Conodont age and biofacies determinations utilize data from seven new collections (table 1) and some older collections (Csejtey and others, 1992, map nos. 9-11 in table 2; ages revised by A.G. Harris, unpub. data, 1994, and reported in Csejtey and others, 1996). Interpretations of depositional environments follow models in Wilson (1975), Mutti and Ricci Lucchi (1978), Cook and others (1983), and Scholle and others (1983). Terrane designations generally follow Silberling and others (1994), except as noted.

SEDIMENTOLOGY, AGE, AND DEPOSITIONAL SETTING

Rocks of the DOs unit within the study area consist chiefly of calcareous and siliciclastic strata of Silurian and probable Silurian age deposited in a deep-water, off-platform setting. Shallow-water shelf or platform rocks have been recognized at several localities; where dated, these strata are earliest Late Devonian and Silurian or Devonian in age.

DEEP-WATER STRATA

Deep-water rocks can be grouped into three broad subunits (subunits A, B, and C) on the basis of lithology and bedding style. Subunit A is found throughout the study area, but subunits B and C are less widespread (fig. 2). Subunit B has been recognized only in the area north of Red Mountain; subunit C crops out in the central part of the study area.

SUBUNIT A

LITHOFACIES

Subunit A consists mainly of thinly interbedded, fine-grained, calcareous metasedimentary rocks, cherty argillite, phyllite, and tuff in various proportions (fig. 3A). It was examined at 8 localities across the study area (fig. 2, locs. 1-8); depositional textures are best preserved at localities 1 and 6 to 8. Most sections are strongly folded; some folds may be slumps. Sections at localities 6 and 7 consist chiefly of fine-grained carbonate; beds are 0.5 to 15 cm (mostly 2-4 cm) thick with abundant parallel laminae and local convolute and low-angle cross laminae. Most carbonate beds are gray to black on fresh and weathered surfaces, but more dolomitic layers weather yellow to olive gray. Carbonate beds consist mostly of micritic to sand-sized anhedral calcite crystals, with 5 to 95 percent euhedral to subhedral dolomite in some layers. Less than 1 percent quartz silt and sand is concentrated in local discontinuous laminae. Some beds are clearly graded; others contain outsize clasts, some of which may be crinoid columnals. Calcite-filled spheres and ovoids that are probably radiolarian ghosts form 2 to 5 percent of fine-grained samples at locality 7.

Black, carbonaceous, noncalcareous argillite, in intervals a few centimeters to several meters thick, is a subordinate part of the sections at localities 6 and 7. It is the predominate lithology at locality 1, where it weathers reddish-brown and forms parallel laminated beds 1 to 4 cm thick with gray phyllitic partings and millimeter- to centimeter-scale, yellow-weathering silty layers. Some beds are quite siliceous, with conchoidal fracture and stylolitic partings. Silty layers are largely quartz; laminae reflect local concentrations of radiolarian ghosts (made up of polycrystalline quartz) and lesser siliceous sponge spicules (fig. 3B).

The section at locality 8 is at least 15 m thick and consists chiefly of 0.5- to 3-cm-thick couplets of steel-gray phyllite and yellow- to tan-weathering siltstone. Sedimentary features include graded and flaser beds and parallel and cross laminae. Coarser grained material in these beds ranges from silt to fine sand and is mostly calcite (30-50%), quartz (30%), and subordinate sedimentary and volcanic lithic grains.

Calcareous siliciclastic rocks also crop out at locality 7, but they are noticably coarser grained and thicker bedded than the rocks at locality 8. The siliciclastic section at locality 7 crops out about 100 m east of the calcareous section described above; the contact between the two lithologies is not exposed. The section consists of about 70 percent orange- to gray-weathering, fine- to medium-grained sandstone, in beds 50 to 120

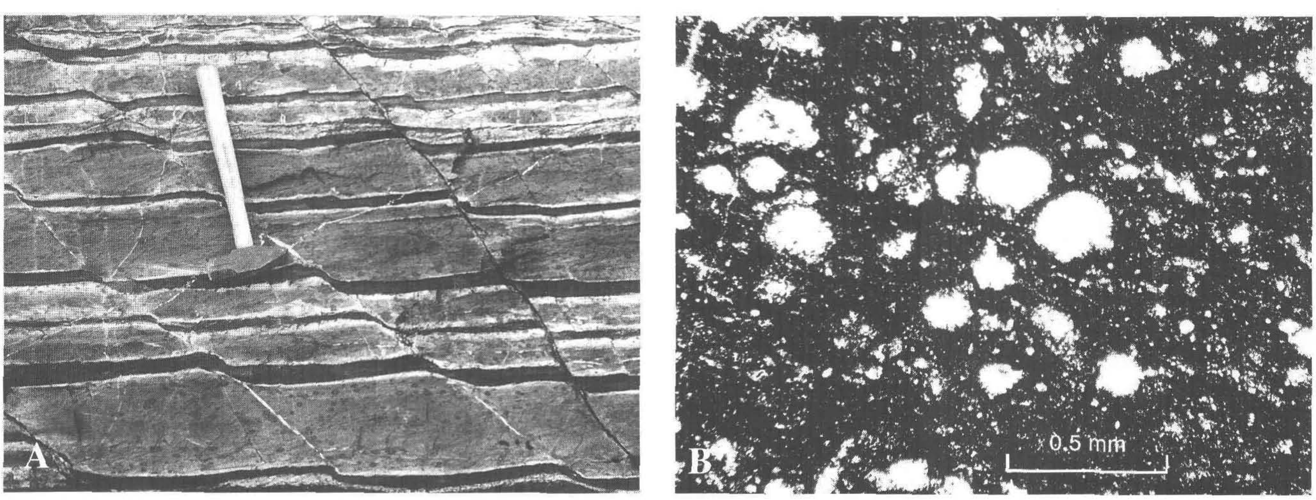

Figure 3. Sedimentary features of DOs subunit A. A, Thinly interlayered, chiefly phyllosilicate material (dark) and carbonate; dark layers contain metamorphic biotite (fig. 2, loc. 3). B, Photomicrograph of carbonaceous siliceous argillite containing abundant radiolarian ghosts made up of polycrystalline quartz (fig, 2, loc. 1).

cm thick, intercalated with gray- to black-weathering thinner beds of siltstone and phyllite. A sample of very fine to fine-grained sandstone consists of calcite (20-30%), quartz (30%), metamorphic lithic grains (10-20%) and phyllosilicate material (10-20%), with minor amounts of sedimentary and volcanic lithic grains, feldspar[1], and biotite.

Thin layers of altered tuff and tuffaceous sediment form a subordinate but notable part of the sections at localities 1, 6, and 8. Layers are a few millimeters to 3 cm thick and weather light to dark green, yellow, or brownish purple. They consist chiefly of euhedral crystals and crystal aggregates of feldspar and quartz in a fine-grained felty groundmass; one sample contains rounded, altered lapilli? (now mostly microcrystalline quartz) as much as 1 mm in diameter.

Pyrite, in 1- to 5-mm crystals and crystal aggregates, is a common minor component of dark, fine-grained calcareous and siliceous beds in subunit A. At locality 8, massive pyrite forms laterally continuous beds 0.5 to 3 cm thick that make up several percent of the outcrop. A grab sample of massive pyrite at this locality yielded 4.8 ppm Ag, 47 ppb Au, 110 ppm Co, 1,495 ppm Cu, 2.4 percent P, 75 ppm Pb, 102 ppm Sb, 39 ppm Se, and 155 ppm Zn.[2]

Rocks south of Red Mountain (fig. 2, locs. 3-5) are similar in general aspect and composition to those described above but have been contact metamorphosed by a small, previously unmapped plug at the snout of the glacier near locality 4. These rocks consist of pinkish-brown- to dark-gray-weathering siliciclastic layers and dark-gray, recessive calcareous layers, intercalated on a scale of 0.5 to 20 cm (fig. 3A). Strata are ductily folded, but locally preserve sedimentary structures such as parallel and cross laminae. Siliciclastic layers contain abundant phyllosilicate material, quartz, and metamorphic biotite. Calcareous layers consist of anhedral calcite with minor laminae of quartz silt.

AGE

Conodont samples were collected from graded, parallel and cross laminated, locally dolomitic metalimestone at localities 6 and 7, but no conodonts were found at either locality. Outcrop patterns (discussed further under "Stratigraphy" below) suggest that subunit A may be older than subunits B and C; this hypothesis implies an age of Silurian or older for subunit A. Lithologic correlations with rocks in the McGrath quadrangle to the southwest (see "Correlation" below) suggest that subunit A could be as old as Cambrian.

[1] DOs thin sections examined in this study were not stained; feldspar grains were recognized petrographically. Most are plagioclase and contain polysynthetic twins.

[2] Au, Co, Se, and Zn determined by induced neutron activation analysis; all other values by inductively coupled plasma-atomic emission spectroscopy. All analyses were performed by ACTLABS.

DEPOSITIONAL ENVIRONMENT

We interpret subunit A as chiefly hemipelagic sediment, with subordinate intercalated turbidites, deposited in a slope and (or) basinal setting adjacent to a continental landmass. Clay-sized "background" material in this facies originated as calcareous peri-platform ooze (Cook and others, 1983) (for example, locs. 6 and 7) or carbonaceous, siliceous, locally radiolarian-rich ooze (loc. 1). Both of these lithologies, but particularly the siliceous strata, have relatively high organic contents and are well-laminated with little or no bioturbation, suggesting that they were deposited in a dysaerobic (poorly oxygenated) to anoxic setting. Few calcareous planktonic organisms existed in the lower Paleozoic (Scholle and others, 1983, p. 622), so fine-grained calcareous material in these deposits must have been derived from a relatively nearby carbonate platform or shelf. Variations in calcareous versus siliceous background material in subunit A thus probably reflect chiefly temporal and (or) spatial differences in proximity to a carbonate source, although differences in depositional setting relative to position of the paleo-CCD (calcite compensation depth) may also be involved.

Millimeter- to centimeter-thick layers of silt and sand punctuate these clay-sized sediments and may have had various origins. Some may be the coarser half of basinal varves formed through cyclic (seasonal?) changes in productivity and (or) detrital influx; others are probably distal turbidites or lags left by bottom currents. Coarser and thicker layers such as those at localities 7 and 8 contain full or partial Bouma sequences and are clearly turbidites. The possible presence of slump folds suggests a slope setting for at least some of this facies.

The semischistose fabric and pervasive calcareous alteration of the turbidites in these facies preclude accurate point counts and thus precise use of point-count-based provenance analyses such as those of Dickinson and Suczek (1979). However, the general composition of subunit A turbidites compared to provenance interpretations by these and other authors (for example, Zuffa, 1980) indicates derivation chiefly from two sources: (1) carbonate platform or shelf (abundant calcareous grains) and (2) continent or continental fragment (abundant quartz). Notable metamorphic and sedimentary lithic grains could have been derived from a continental and (or) a subduction complex (accretionary prism) source. Volcanic lithic grains, as well as the discrete tuffaceous layers found throughout this facies, suggest some input from a volcanic arc.

SUBUNIT B

LITHOFACIES

Subunit B is characterized by abundant siliciclastic strata, includes thin layers of fine-grained carbonate and altered ash, and was studied at localities 9 to 11 (fig. 2). A folded section 8 to 10 m thick at locality 9 consists chiefly of thin-bedded carbonate and subordinate thick-bedded siliciclastic rocks; sections 30 and 50 m thick at localities 10 and 11 comprise carbonate beds intercalated with 20 to 30 and 50 to 60 percent siliciclastic strata, respectively. Thus, thick-bedded siliciclastic strata are ubiquitous in subunit B and are consistently intercalated with carbonate rocks; similar siliciclastic rocks in subunit A are rare and, where found, are not interbedded with carbonate strata.

Siliciclastic rocks at all three localities in subunit B are medium-gray, gray- to brown- to reddish-brown-weathering siltstone to fine-grained sandstone. Beds are chiefly 30 cm to 1.5 m thick (fig. 4A); amalgamated beds as much as 3 m thick punctuated by thin mud drapes and mud chip layers (chips as much as 7 cm long) were noted at locality 11. Sedimentary structures in these rocks include common parallel and cross lamination, and local convolute laminae and flame structures. Some bed bottoms display abundant and well-preserved flutes (as large as 3 x 10 cm) and grooves (as large as 3 cm x 2 m) (fig. 4B). Coarser grained beds are clearly graded and have erosive, locally channeled, bases. Some beds contain 1- to 3-mm-thick horizontal trace fossils.

Eight siliciclastic samples from localities 9 to 11 were examined in thin section; their composition is quite uniform (fig. 4C, D) and is similar to that of the siliciclastic beds in subunit A (loc. 7). Sorting is poor to very poor; grains are chiefly subangular, but some are rounded. Quartz, mostly monocrystalline grains with straight extinction, is the major siliciclastic component and makes up 20 to 40 percent of all samples. Carbonate material (including monocrystalline and

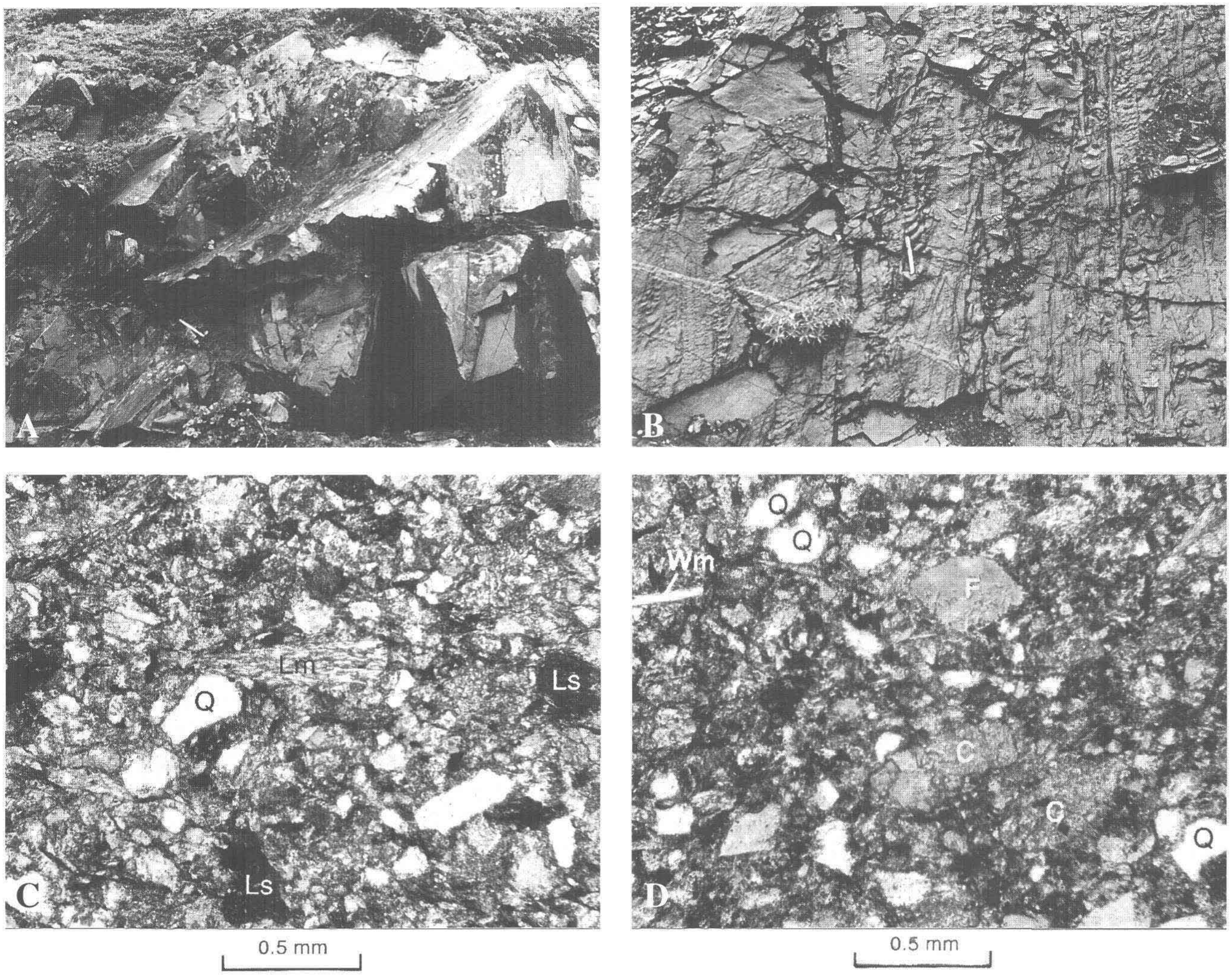

Figure 4. Sedimentary features of DOs subunit B. A, Thick-bedded fine-grained calcareous siliciclastic turbidites (fig. 2, loc. 11). B, Base of calcareous siliciclastic turbidite bed with abundant flutes and grooves (fig. 2, loc. 10). C and D, Photomicrographs of fine-grained calcareous siliciclastic turbidites (fig. 2, loc. 11); samples contain about 30 percent and 50 percent carbonate material, respectively. C, polycrystalline calcite fragment; F, feldspar; Lm, metamorphic rock fragment; Ls, sedimentary rock fragment; Q, quartz; Wm, white mica.

polycrystalline clasts, cement, and patchy replacement of feldspar and lithic grains) constitutes 15 to 50 percent. Other clasts include feldspar (trace to 5%), metamorphic lithic clasts such as phyllite and fine-grained schist (5-15%), and sedimentary lithic clasts such as mudstone and siltstone (5-15%). Volcanic lithic clasts and white mica are minor (<5%) but ubiquitous components of all samples; rare constituents include dolomite, chert, biotite, chlorite, and tourmaline. Fine-grained phyllosilicate matrix and pseudomatrix is pervasive, and makes up as much as 20 to 30 percent of the least calcareous samples. Original sedimentary fabric is better preserved in the siliciclastic strata of subunit B than in compositionally similar rocks in subunits A and C.

Very dark gray to black, light- to medium-gray-weathering calcareous layers are most abundant at locality 9, where they are 1 to 10 cm thick (fig. 5A) and contain obvious parallel and cross laminae (fig. 5B); cross-sets are low angle and less than 1 cm thick. All five samples of this lithology consist of calcitized radiolarite (fig. 5C), similar to, but richer in radiolarians than, the radiolarian-bearing beds in subunit A (locality 7). Radiolarians are chiefly ovoids and spheres, 150 to 300 μm in maximum diameter, that make up 5 to 40 percent of the samples. Most are filled with finely crystalline calcite or, less commonly, with calcite and chalcedony or chalcedony alone. Some contain concentrations of organic material that preserve details of the original test structure. Other bioclasts in these samples include calcareous sponge spicules (as much as 80 μm wide and 2.5 mm long), possible ostracodes, and a few unidentifiable fragments.

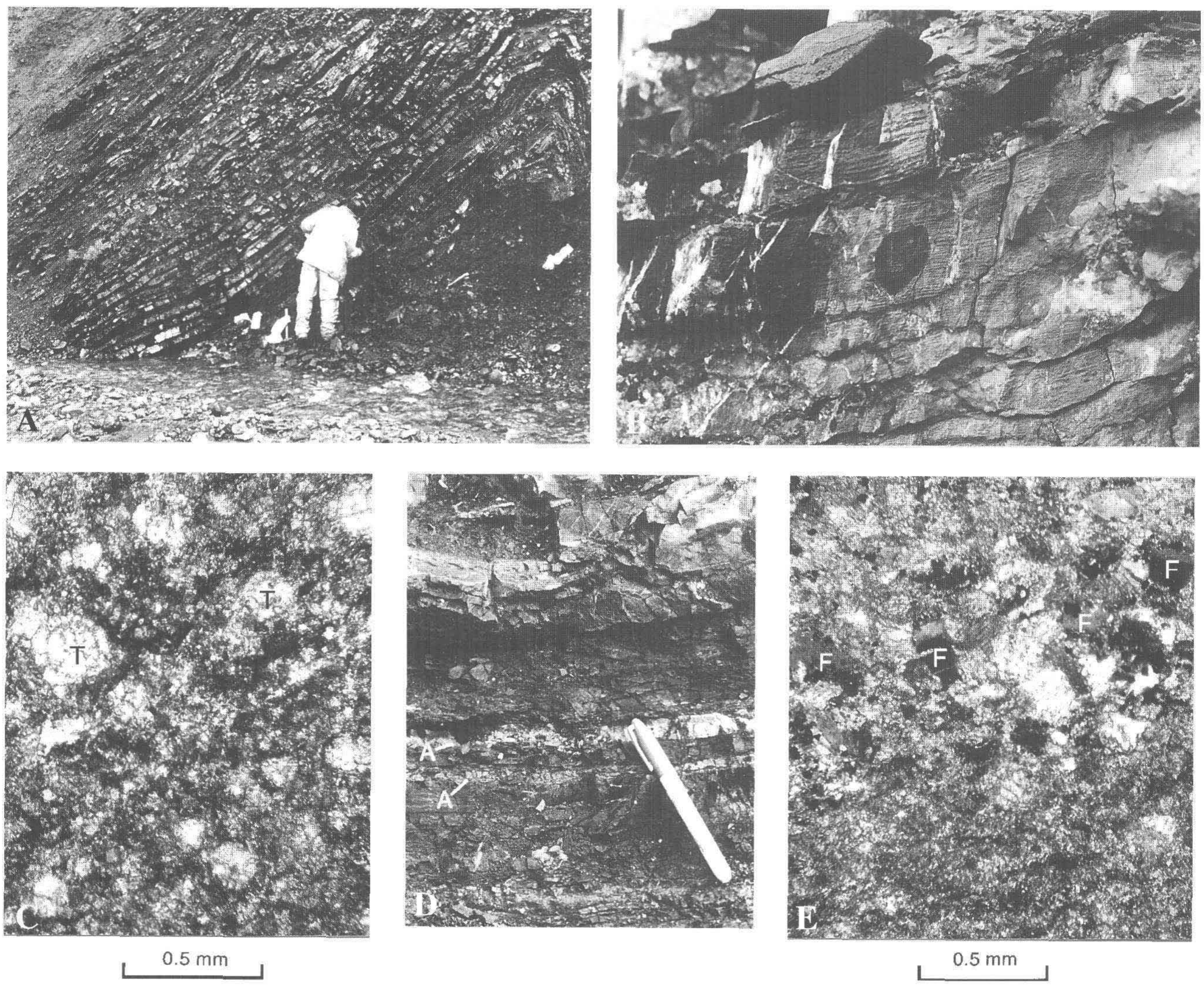

Figure 5. Sedimentary features of DOs subunit B (fig. 2, loc. 9). A-C, outcrop views and photomicrograph (C) of thin-bedded calcitized radiolarite that yielded conodonts of probable Silurian age. Note parallel and cross laminae in B, and locally preserved details of original test structure (T) in C. Outcrop view (D) and photomicrograph (E) (crossed nicols) of altered ash layers (A) intercalated with calcitized radiolarite. Note abundant feldspar crystals (F) in E.

The radiolarians and other bioclasts float in a matrix of very finely crystalline calcite, dolomite, and dark (organic?) material; crystals of calcite and dolomite are mostly 50 µm and less. The lamination in these samples reflects differing concentrations of radiolarians, dolomite, and (or) organic material.

Gray calcareous layers at localities 10 and 11 are 40 cm and less (mostly 8 cm and less) thick with parallel and cross laminae. Layers consist of recrystallized micrite; laminae concentrate various amounts of dolomite, organic material, quartz silt, and (or) phyllosilicate material.

Altered ash layers were noted at localities 9 and 10 in outcrop and thin sections. In outcrop, they are a few millimeters to 2 cm thick, have a friable, pasty, or indurated texture, and may be white, ivory, yellow, light gray, orange, red, or reddish brown. At least 12 discrete ash layers are intercalated with calcitized radiolarite through a 1.6-m-thick interval at locality 9 (fig. 5D), and a single 1-cm-thick pasty yellow ash layer was noted near the base of the section at locality 10. Abundant euhedral zircons were recovered from one ash at locality 9. Thin sections of calcitized radiolarite from locality 9 and of recrystallized micrite from locality 10 contain irregular lenses and laminae of ash, from 1 mm to a few hundred microns thick, rich in sand- and silt-sized euhedral to subhedral grains of feldspar (some zoned) and quartz (fig. 5E).

AGE

Conodonts from two collections of parallel- and cross-laminated calcitized radiolarite at locality 9 consist exclusively of elements of *Ozarkodina excavata*, which ranges from the late Early Silurian into the late Early Devonian (Wenlockian to early Emsian) (table 1, fig. 6A-F). We consider these collections to be of of probable Silurian age; if they were Devonian, they would most likely include other conodont taxa in addition to *O. excavata*. *O. excavata* is a eurytopic species that is the most abundant (and often the only) conodont in hemipelagic basinal deposits of post-Llandoverian Silurian age.

Figure 6.➤ Silurian and Devonian conodonts from metacarbonate rocks in Denali National Park (A-V and DD-II) and correlative rocks in the McGrath C-1 quadrangle (W-CC), Alaska (scanning electron micrographs; illustrated specimens are reposited in the U.S. National Museum, USNM, Washington, D.C.). See table 1 for faunal analysis, age assignment, and lithostratigraphic description of samples and figure 2 for geographic and geologic position of Denali localities.

A-F, *Ozarkodina excavata* (Branson and Mehl), two Pa, Pb, M, Sb, and Sc elements, lateral views, A-E x50 and F x80, USNM 491604-09; loc. 9, subunit B of deep-water facies, USGS colln. 12537-SD.

G, Distomodontid? M? element, lateral view, x100, USNM 491610; loc. 15, subunit C of deep-water facies, USGS colln. 12533-SD.

H-K, N, Loc. 16, subunit C of deep-water facies, USGS colln. 12532-SD.

H, *Ozarkodina* sp., Pa element, lateral view, x100, USNM 491611.

I, *Walliserodus* sp., outer lateral view, x100, USNM 491612.

J, *Panderodus unicostatus* (Branson and Mehl), inner lateral view, x75, USNM 491613.

K, Unassigned Sb compressed coniform element of Early Silurian morphotype, x100, USNM 491614.

N, *Belodella* sp., Sc element, outer lateral view, x100, USNM 491617.

L, *Panderodus unicostatus* (Branson and Mehl) inner lateral view, x75, USNM 491615; loc. 14, subunit C of deep-water facies, USGS colln. 12535-SD.

M, Distomodontid or icriodellid P element fragment, upper view, x100, USNM 491616; loc. 15, subunit C of deep-water facies, USGS colln. 12534-SD.

O-Q, Distomodontid and (or) pelekysgnathid coniform S elements; subunit C of deep-water facies.

O, Inner lateral view, x100, USNM 491618; loc. 15, USGS colln. 12534-SD.

P, Q, Anterior and oblique lower views, x60 and x75, USNM 491619-20; loc. 14, USGS colln. 12535-SD.

R-T, Unassigned compressed alate coniform elements of Early Silurian morphotype, Pb? element (outer lateral view), M element (posterior view), and Sb element (inner lateral view), x90, USNM 491621-23; loc. 14, subunit C of deep-water facies, USGS colln. 12535-SD.

U, V, *Panderodus* sp. element and Sb element *Belodella*? sp., outer lateral views, x100, USNM 491624-25; loc. 18, shallow-water facies, USGS colln. 12531-SD.

W, X, Distomodontid and (or) pelekysgnathid coniform S elements (like O-Q), lateral views, x100, USNM 491626-27; from 353-m-thick section of black to very dark gray micrite on north side of Dillinger River (SW1/4 sec. 6, T. 28 N., R. 20 W.), McGrath C-1 quadrangle, 86 m above base of section, USGS colln. 9736-SD.

Y-CC, Unassigned compressed alate coniform elements of Early Silurian morphotype (like R-T), x100; same locality as W.

Y, Z, CC, Pb?, M, and Sc elements, outer lateral and two inner lateral views, USNM 491628-30; same collection as W.

AA, BB, Sa and Sb elements, posterior and inner lateral views, USNM 491631-32; USGS colln. 9738-SD, 126 m above base of section.

DD-GG, *Playfordia primitiva* (Bischoff and Ziegler), P elements, lower, lateral, and upper views of one specimen, x60, and upper view of another, x75, USNM 491633-34; loc. 19, shallow-water facies, USGS colln. 12358-SD.

HH, *Mesotaxis asymmetrica* (Bischoff and Ziegler), Pa element, upper view, x60, USNM 491635; same collection as DD.

II, *Icriodus subterminus* Youngquist, narrow morphotype, P element, upper view, x75, USNM 491636; same collection as DD.

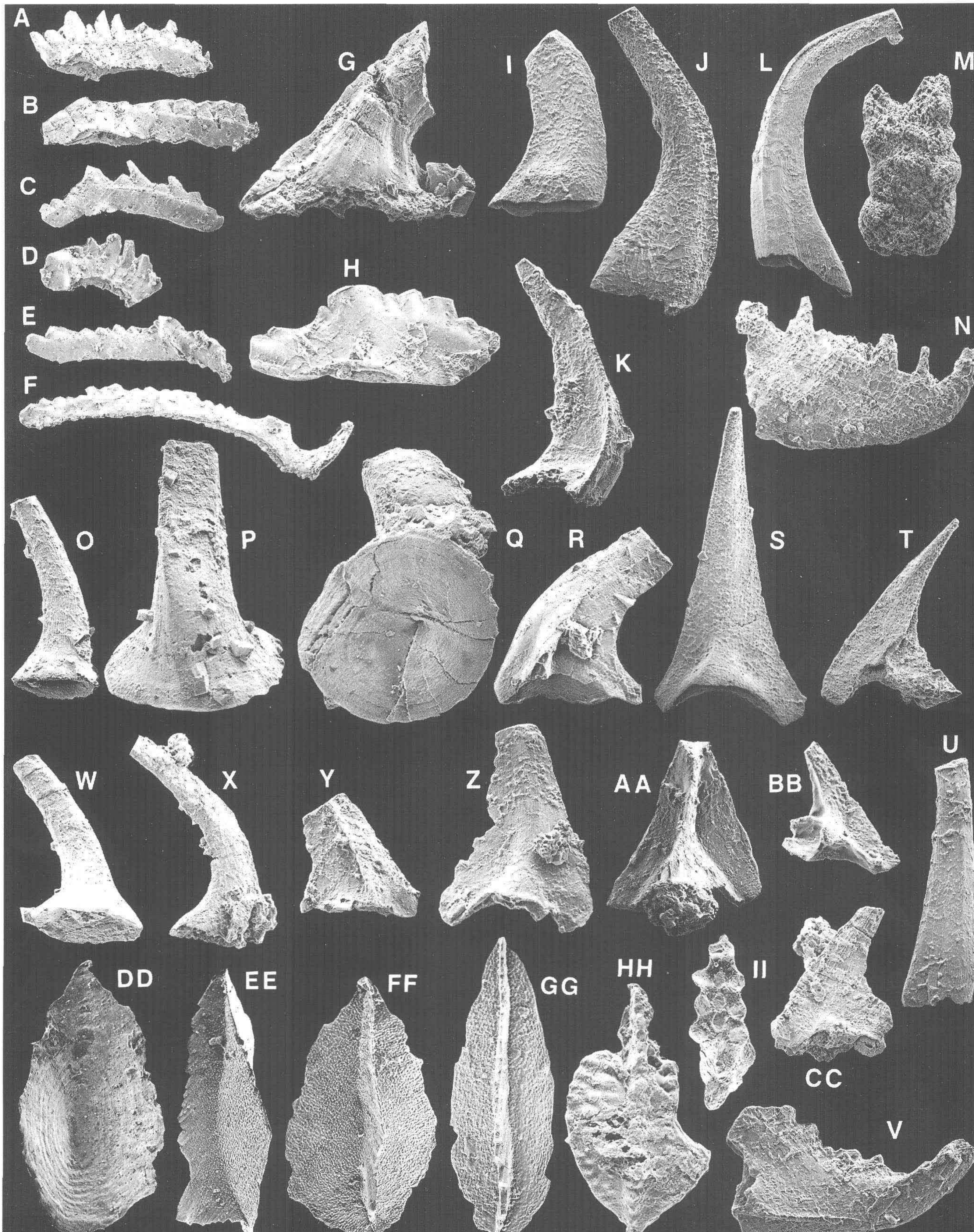
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Table 1. Conodont data for localities shown on figure 2.

[Letters in field number refer to collector: AD, J.A. Dumoulin; Cy, Béla Csejtey, Jr. Abbreviations: CAI, color alteration index; indets., indeterminate bar, blade, platform, and coniform fragments]

LOCALITY NO., (FACIES; SUBUNIT)	QUADRANGLE LATITUDE/ LONGITUDE	CONODONT FAUNA AND CAI (FIELD NO.; USGS COLLN. NO.)	AGE	BIOFACIES	REMARKS
9 (Deep-water facies; subunit B)	Mt. McKinley B-1 63°21'18"/ 150°18'38"	5 Pa elements *Ozarkodina excavata* (Branson and Mehl) 2 indets. CAI=5-5.5 (96AD8X; 12536-SD)	late Early Silurian into late Early Devonian (Wenlockian-early Emsian), probably Silurian—if collection was Devonian in age, other taxa would probably be represented.	Indeterminate (too few conodonts); probably deep-water open-marine setting.	Five-cm-thick bed of very dark-gray to black, light- to medium-dark-gray-weathering, parallel- to cross- laminated, calcitized radiolarite. From 10-m section of mostly thin-bedded, calcitized radiolarite with subordinate thick-bedded calcareous siliciclastic turbidites. Collected a few meters downstream from 96AD8Y. Sample weight 14.8 kg.
		Ozarkodina excavata (Branson and Mehl) (fig. 6A-F) 9 Pa, 4 Pb, 4 M, 4 Sb and 9 Sc juvenile to adult elements 33 fragments most probably of *O. excavata* CAI=5-5.5. (96AD8Y; 12537-SD)		*O. excavata* biofacies; this eurytopic, long-lived form is typically the most abundant or often the only conodont species recovered from deep-water, hemipelagic basin deposits of Wenlockian and younger Silurian age.	Same lithology as 96AD8X; 10-cm-thick bed within 1.6-m-thick measured section. Sample weight 13.4 kg.
14 (Deep-water facies; subunit C)	Mt. McKinley B-1 63°25'14"/ 150°01'25"	21 distomodontid and (or) pelekysgnathid coniform elements (fig. 6P, Q) 3 Pb, 1 M, and 1 Sb unassigned compressed alate coniform elements (fig. 6R-T) 8 *Panderodus unicostatus* (Branson and Mehl) elements (fig. 6L) 11 indets. CAI=5 (96AD7C; 12535-SD)	Early Silurian (late Llandoverian-Wenlockian). The compressed alate coniforms could belong to a new genus or to Silurian genera such as *Distomodus* or *Pterospathodus*. Coniform elements and more roundiform distomodontid and (or) pelekysgnathid coniforms like those in this collection were reported by Dumoulin and Harris (1988, figs. 4C-I) from the Ambler River quadrangle, Alaska, and considered Wenlockian or Ludlovian in age. Virtually the same fauna (fig. 6W-CC) is found in three collections from the McGrath C-1 quadrangle (Armstrong and others, 1977; USGS colln. 9736-38-SD) and are here considered late Llandoverian to Wenlockian in age. Similar coniform elements were also found in the late Llandoverian part of the Chicotte Formation on Anticosti Island, Québec (Uyeno and Barnes, 1983) but were not assigned to any taxon.	Postmortem transport from shallow-water depositional environment(s); all specimens are small and platform elements are notably absent.	Carbonate conglomerate containing micrite and dolomite clasts as much as 7 cm in size; some clasts contain radiolarian ghosts. Bed is 80 cm thick and has scoured base. Collected about 5 m above base of 21-m-thick measured section consisting of carbonate turbidites, debris flows, and hemipelagic "background" sediment. Sample weight 12.3 kg.

Table 1. Conodont data for localities shown on figure 2—Continued.

15 (Deep-water facies; subunit C)	Healy B-6/Mt. McKinley B-1 63°24'50"/ 150°00'00"	3 robust distomodontid element fragments of Llandoverian-Ludlovian morphotype (fig. 6G) 3 indets. CAI=5-5.5 (96AD4C; 12533-SD)	Early to early Late Silurian (Llandoverian-Ludlovian).	Indeterminate (too few conodonts); postmortem transport from shelf or platform depositional environment. Conodonts are tectonically deformed and fractured.	Sooty, black, laminated to cross-laminated dolomitic micrite in beds 2 mm to 4 cm thick. Sample weight 6.2 kg.
	Mt. McKinley B-1 63°24'48"/ 150°00'02"	1 P element fragment of a distomodontid or icriodellid (fig. 6M) 5 *Panderodus* sp. elements 2 distomodontid or pelekysgnathid coniform elements (fig. 6O) 1 unassigned M element of post-Ordovician morphotype 1 indet. CAI=5-5.5 (96AD4G; 12534-SD)	Silurian (Wenlockian, possibly early Wenlockian). The earliest pelekysgnathids and latest icriodellids overlap in the early Wenlockian. If the coniforms are distomodontids, an early Wenlockian age is still likely as these could belong in *Distomodus? dubius* (Rhodes).	Indeterminate (too few conodonts); coniform elements were probably derived from shallow-water depositional environments.	Black to light-gray, grayish-orange-weathering, massive carbonate conglomerate at least 20 m thick. Clasts up to 5 cm across are micrite and dolomite; matrix mostly dolomite. Some clasts contain relict fossils including possible algae. This sample may be from a channel cut into the deposits represented by 96AD4C. Sample weight 14.1 kg.
16 (Deep-water facies; subunit C)	Healy B-6 63°25'19"/ 149°55'05"	*Belodella* sp. 1 Sa and 3 Sc elements (fig. 6N) 1 ozarkodinid? Sb (plectospathodan) element of Silurian-Devonian morphotype 1 Pa *Ozarkodina* sp. (fig. 6H) 4 *Panderodus unicostatus* (Branson and Mehl) elements (fig. 6J) 1 pelekysgnathid? coniform element 2 *Walliserodus* sp. elements (fig. 6I) 1 Sb compressed coniform element of Early Silurian morphotype (fig. 6K) 10 indets. CAI=5 (96AD3D; 12532-SD)	Early Silurian (probably Wenlockian)	Indeterminate (too few conodonts); postmortem transport from shelf or platform depositional environment(s).	Dark-gray to black, medium-gray-weathering, fetid dolomitic limestone from 10 to 30-cm-thick graded bed containing chiefly micritic clasts (as much as 5 cm in diameter) and some dolomitic clasts and fossil fragments (colonial corals and crinoids?) in dolomitic matrix; partly cross laminated in upper part of bed. Collected 2 m above base of 42-m-thick measured section of thin-to thick-bedded carbonate turbidites intercalated with calcareous hemipelagic "background" sediments. Sample weight 10.1 kg.
18 (Shallow-water facies)	Healy B-6 63°25'18"/ 149°55'02"	1 Sb element *Belodella*? sp. (fig. 6V) 4 *Panderodus* sp. elements (fig. 6U) 4 indets. CAI=5-5.5 (96AD2G; 12531-SD)	Silurian or Devonian; no younger than earliest Late Devonian (earliest Frasnian).	Indeterminate (too few conodonts); relict peloidal texture and spar-filled fenestral fabric seen in thin-section indicates shallow-water depositional environment.	Medium- to light-gray and pinkish-gray, massive, mottled dolostone bed 1.6 m thick in base of 16-m-thick measured section; sample from basal 20 cm. Sample weight 8.4 kg.

Table 1. Conodont data for localities shown on figure 2—Continued.

LOCALITY NO., (FACIES; SUBUNIT)	QUADRANGLE LATITUDE/ LONGITUDE	CONODONT FAUNA AND CAI (FIELD NO.; USGS COLLN. NO.)	AGE	BIOFACIES	REMARKS
19 (Shallow-water facies)	Healy B-6 63°25'16"/ 149°54'43"	*Belodella devonica* (Stauffer)? 2 Sa and 2 Sb elements *Dvorakia*? cf. *D.* sp. of Klapper and Barrick, 1983 1 Sb, 2 Sc, and 1 Sd elements 20 P elements *Icriodus subterminus* Youngquist, narrow morphotype (fig. 6II) 4 Pa element fragments *Mehlina* sp. 1 Pa element *Mesotaxis asymmetrica* (Bischoff and Ziegler) (fig. 6HH) 62 P elements *Playfordia primitiva* (Bischoff and Ziegler) (fig. 6DD-GG) 81 Pa elements of *Polygnathus*, chiefly *Po. aequalis* Klapper and Lane 18 Pa element fragments *Polygnathus* spp. indet. 148 indets. CAI=5 (94ACY-6a; 12358-SD)	earliest Late Devonian (early Frasnian; upper part of Lower *Mesotaxis falsiovalis* Zone into the *Palmatolepis punctata* Zone). *Playfordia primitiva* is the most biostratigraphically restricted conodont in the fauna and is best known from the *Pa. transitans* and succeeding *Pa. punctata* Zones of Ziegler and Sandberg (1990). A list of conodont and brachiopod species from locality 19 is given in Savage and others (1995) and Csejtey and others (1996); these authors also considered the faunas early Frasnian in age.	Postmortem transport within the playfordid-polygnathid biofacies; normal-marine, probably middle shelf near shallow-shelf depositional setting because of relative abundance of small icriodid platform elements. *Playfordia primitiva* is generally a rare though cosmopolitan component of early Frasnian faunas. Its unusual abundance here suggests this locale lay within its preferred habitat.	Massive, medium-dark-gray to black, light- to medium-gray-weathering, fine-grained fossiliferous limestone that is sheared and partly recrystallized; fossils include solitary and colonial corals, brachiopods, gastropods, and pelmatozoan fragments. Sample weight 11.2 kg.

DEPOSITIONAL ENVIRONMENT

We interpret subunit B as turbidites, probably deposited in a submarine fan or fan complex, intercalated with subordinate hemipelagic deposits. Hemipelagic layers originated chiefly as calcareous peri-platform ooze; they contain locally common, largely calcitized radiolarians. The turbidites are similar in general aspect to those in subunit A but are more abundant. They represent facies B, C, and D of Mutti and Ricci Lucchi (1978), an association most typical of an outer fan setting. Their composition is also similar to the turbidites in subunit A, suggesting a similar mixed provenance of carbonate platform or shelf, continent, and volcanic arc.

PALEOCURRENT DATA

Paleocurrent data were obtained from subunit B at two locations (fig. 7). The more reliable and conclusive results are from locality 11, where 6 flutes, 5 grooves, and 9 cross laminae give a visual mean direction of about 195°. As products of the upper flow regime, the flutes and grooves are likely to be more meaningful than the more scattered cross laminae. Bedding at locality 11 is upright and dips 30 to 60°; beds and sedimentary structures were restored to horizontal by the standard single-tilt rotation (see, for example, Potter and Pettijohn, 1977, p. 372). There is little risk of significant paleocurrent error with moderate bedding dips such as these. Less reliable but broadly similar results were obtained from 2 grooves and 3 cross laminae at locality 10, which give a visual mean paleocurrent direction of about 135°. Bedding dips 45 to 55° and is overturned. For lack of any evidence for a more complex retrodeformation path, the standard single-tilt rotation was used here as well, but the chances of a substantial paleocurrent error are much greater than at locality 11 because the beds are overturned.

SUBUNIT C

LITHOFACIES

Subunit C consists mainly of thin-bedded to massive, fine-grained to conglomeratic calcareous metasedimentary rocks; it was studied at localities 12 to 16 (fig. 2). Thick-bedded to massive, coarse-grained to conglomeratic carbonate rocks, not observed in subunits A and B, are the distinguishing feature of subunit C and are found at all 5 localities. Calcareous siliciclastic rocks and altered tuffs and tuffaceous sediment are notable intercalated lithologies at locality 15.

Original sedimentary features are best preserved at localities 14 and 16, at which sections of 21 and 42 m, respectively, were measured. At locality 14, beds are chiefly 0.5 to 10 cm thick, with subordinate thick-bedded to massive intervals 0.8 to 5 m thick. At locality 16, beds range from less than 1 cm to 1.5 m thick, but about one-third of the section consists of 30- to 70-cm-thick beds. Grain-size at both localities ranges from micrite to clast- and matrix-supported conglomerate with clasts as much as 12 cm long (fig. 8A); conglomeratic beds range from less than 5 cm to at least 5 m thick. Many beds are graded (fig. 8B); some of these are at least 60 to 70 m in lateral extent. Some coarser beds have scoured bases with as much as 0.5 to 2 cm of relief; other coarse beds are amalgamated. Finer grained intervals contain abundant parallel and rare cross and convolute laminae.

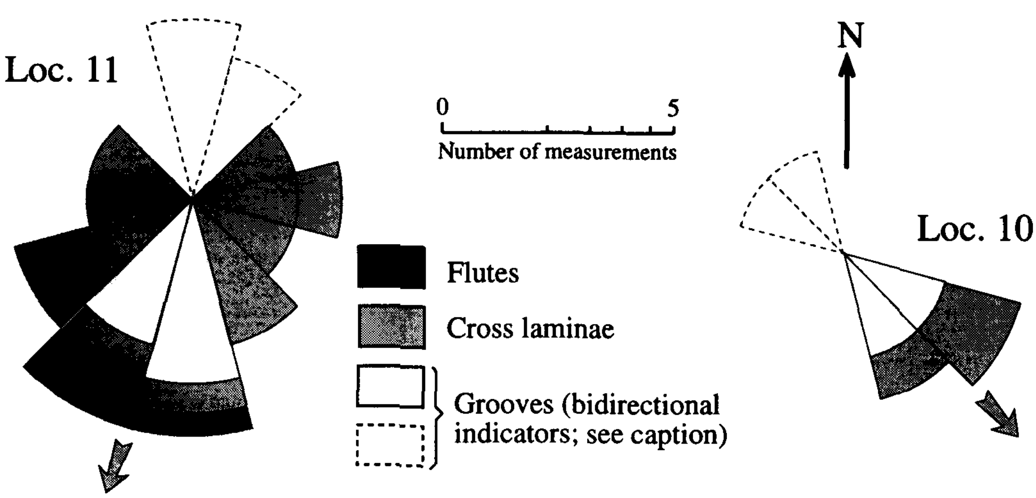


Figure 7. Paleocurrent rose diagrams for calcareous siliciclastic turbidites of DOs subunit B at two localities (fig. 2, locs. 10, 11) in Denali National Park. Arrows showing inferred paleoflow directions are visual estimates of vector mean. Grooves record line of paleoflow but not azimuth (for example, 40° or 220°). Rose petals representing grooves are dashed on side opposite from inferred paleoflow azimuth.

Clasts are typically rounded to elongate and locally imbricated; some contain parallel laminae. Most clasts have irregular outlines and appear to have been relatively unlithified when deposited; these clasts were probably partially cemented during early diagenesis. Most samples contain micritic and lesser dolomitic clasts in a chiefly dolomitic matrix (figs. 8C and D). Some clasts consist of rare, fine-grained bioclasts in a micritic matrix; bioclasts include probable dasycladacean algae, crinoidal debris, and calcitized radiolarians. Other clasts, commonly silicified, consist of single sand- to pebble-sized fragments of colonial coral and (or) stromatoporoids. Siliciclastic material is rare or absent in these sections.

At locality 15, however, thin-bedded to massive metacarbonate is intercalated at several scales with orange- and gray-weathering calcareous siliciclastic strata (fig. 9). Three sequences, each consisting of 20 to 50 m of relatively pure carbonate rocks overlain by an equivalent or slightly thicker interval of more siliciclastic strata, are clearly visible on cliff faces at this locality; the highest sequence is capped by massive carbonate. It is unclear whether these sequences are structural or stratigraphic repeats—only the lowermost of the three sequences is accessible and was examined and sampled for this study.

In this lowermost sequence, the lower, carbonate interval consists of two dissimilar lithologies that appear to be laterally equivalent. The first is a 20-m-thick section of thick-bedded to massive, clast- and matrix-supported carbonate conglomerate similar to that described above from localities 14 and 16. Clasts (as much as 5 cm long) are chiefly micritic and float in a dolomitic matrix; some clasts contain relict algal(?) bioclasts. The second lithology is yellowish-gray to

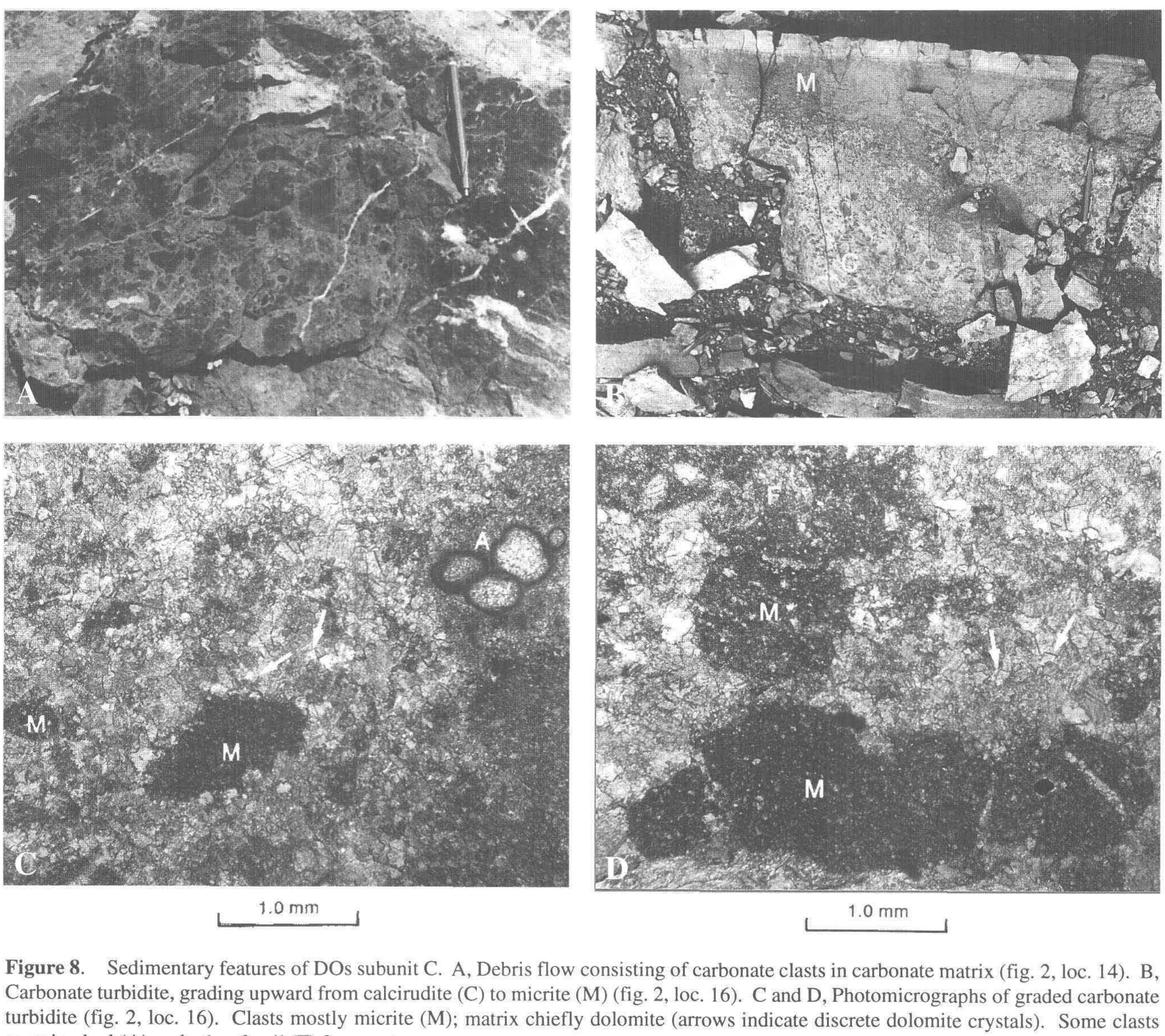


Figure 8. Sedimentary features of DOs subunit C. A, Debris flow consisting of carbonate clasts in carbonate matrix (fig. 2, loc. 14). B, Carbonate turbidite, grading upward from calcirudite (C) to micrite (M) (fig. 2, loc. 16). C and D, Photomicrographs of graded carbonate turbidite (fig. 2, loc. 16). Clasts mostly micrite (M); matrix chiefly dolomite (arrows indicate discrete dolomite crystals). Some clasts contain algal (A) and other fossil (F) fragments.

black, locally dolomitic and (or) carbonaceous micrite in thin beds (most 0.5-4 cm, rarely as much as 10 cm) with abundant parallel laminae and locally scoured bases.

The upper, more siliciclastic interval of the lowermost sequence is more than 100 m thick and consists chiefly of subequal amounts of gray- to black-weathering phyllite and siltstone and tan- to orange-weathering calcareous siltstone to fine-grained sandstone. Beds are generally ≤20 cm thick and graded, with parallel and cross lamination. Sandstones are similar to those described above in subunit B but are more calcareous (50-95%) and proportionately richer in feldspar and volcanic lithic clasts; grains with both felsitic and lathwork volcanic textures were noted. Subordinate lithologies in this interval (<5% each) include black carbonaceous argillite, black dolostone, and orange- to red-weathering tuffaceous sediment. Argillite and dolostone form 1 to 6 m intervals of thin (<3 cm) beds. Tuffaceous layers are a few centimeters to several decimeters thick and medium grained to pebbly; they grade upward into calcareous siltstone and phyllite and contain abundant highly altered feldspar laths.

AGE

Four samples from three localities in this facies yielded conodonts (table 1, fig. 6). Conodonts of Early Silurian (late Llandoverian-Wenlockian) age were obtained at locality 14 from a conglomerate bed 80 cm thick of (dolo)micritic clasts as much as 7 cm long in a dolomitic matrix. At locality 15, a few deformed distomodontid element fragments were recovered from 3-cm-thick beds of carbonaceous dolomitic micrite; massive carbonate conglomerate at least 20 m thick at this same locality produced conodonts of early(?) Wenlockian age. The collections from locality 14 and the conglomerate at locality 15 contain coniform elements derived from shallow-water biofacies (fig. 6O-T). At locality 16, a conglomerate bed 20 to 30 cm thick of coral fragments and (dolo)micritic clasts as much as 5 cm long in a calcareous matrix produced a mixture of Early Silurian (probably Wenlockian) coniform conodonts representing a range of shelf or platform depositional environments.

We believe that the conodonts recovered from subunit C accurately date the subunit and were not reworked from significantly older beds. Although conodonts in this subunit have been redeposited—most are shallow-water forms transported, chiefly by turbidity currents, into a deeper water setting—several lines of evidence suggest that the shallow-water source facies and the deeper water depositional facies were essentially coeval. As noted above, most carbonate clasts in subunit C were relatively unlithified when deposited, indicating that clast transport took place soon after initial sedimentation of the clast material. In addition, both coarse-grained redeposited beds (table 1, locs. 14, 15 [sample 12534-SD], and 16) and fine-grained hemipelagic "back-

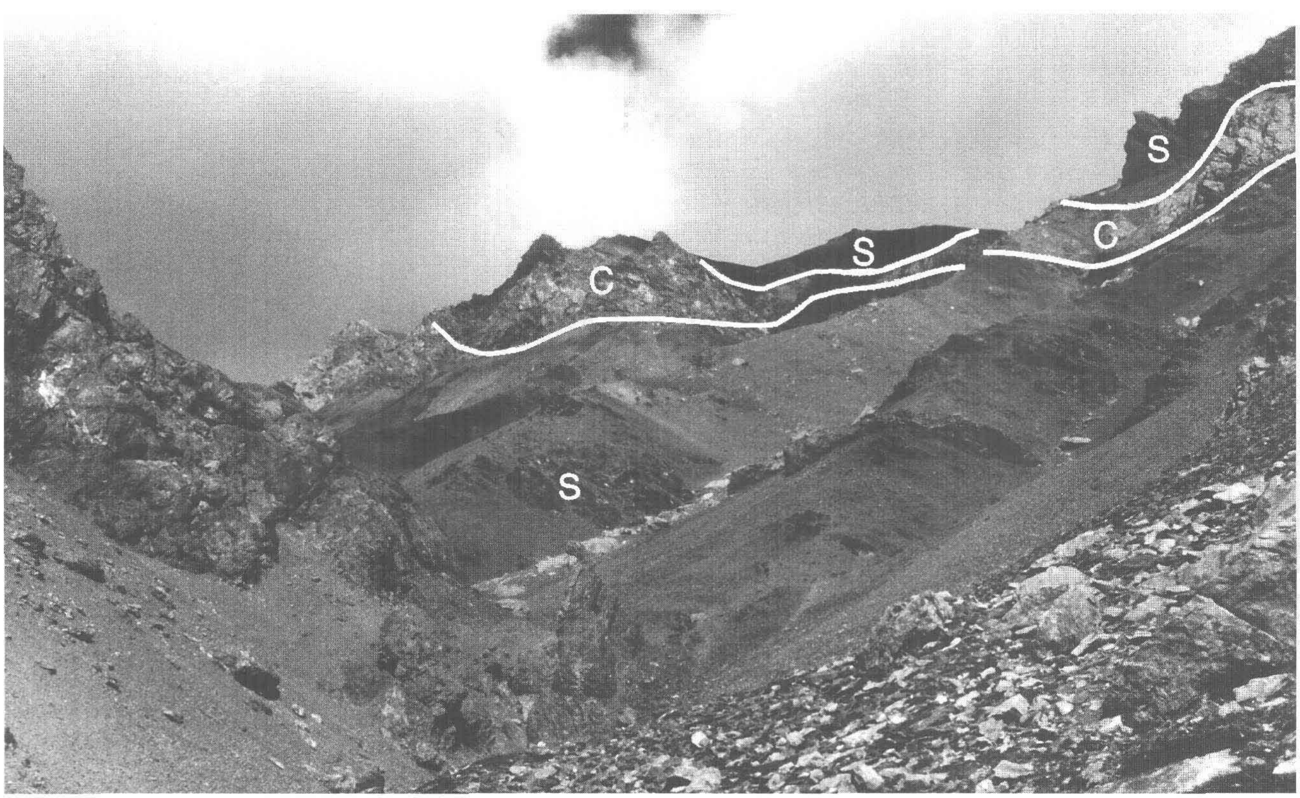


Figure 9. Alternations of massive carbonate (C) and thin-bedded, more siliciclastic rocks (S) (fig. 2, loc. 15). Cliff face is about 200 m high.

ground" material (table 1, loc. 15, sample 12533-SD) in this subunit yield relatively similar conodont faunas. Regional correlations, however, suggest that subunit C could be at least in part of Late Silurian or younger age; this possibility is discussed further below.

DEPOSITIONAL ENVIRONMENT

Turbidites and debris flows (clast- and matrix-supported carbonate conglomerate) derived almost exclusively from a carbonate platform and (or) shelf source form the bulk of this unit. Clasts of calcareous radiolarite in some beds indicate input from coeval slope and (or) basinal sediments. Locally (loc. 15), calcareous strata are overlain by siliciclastic turbidites (with a mixed provenance like that interpreted for turbidites in subunits A and B) intercalated with subordinate tuffaceous and calcareous hemipelagic layers. Submarine fans composed of carbonate detritus are rare (Cook and others, 1983; Scholle and others, 1983), and the carbonate turbidites and debris flows in subunit C probably accumulated in slope and (or) base-of-slope aprons. Aprons are laterally more continuous and internally less organized than fans; they characterize carbonate margins because such margins act as "line" rather than "point" sources (Scholle and others, 1983, pp. 567-569).

SHALLOW-WATER FACIES

Rocks that apparently formed in relatively shallow-water settings have been recognized at several localities within DOs (fig. 2, locs. 17-20). All of these fall within the "massive limestone interbed" mapped by Csejtey and others (1992, p. 27).

Massive, light- to medium-gray-weathering, medium-dark-gray to black dolomitic metalimestone at locality 19 contains brachiopods and conodonts of early Frasnian age (Savage and others, 1995; Csejtey and others, 1996; this report, table 1 and fig. 6DD-II), as well as solitary and colonial corals, gastropods, pelmatozoan and trilobite(?) fragments, red algae, and calcispheres (figs. 10A-C). Most samples are bioclastic-peloidal wackestones and packstones; some skeletal fragments have micritic rims (fig. 10C). These rocks form an interval about 20 to 30 m thick and overlie at least 50 m of black shale (fig. 10A). Dark gray, nodular, argillaceous carbonate beds near the top of this shale contain an early Frasnian conodont and brachiopod fauna similar to that in the massive metalimestone (Savage and others, 1995).

Fossils and sedimentary features at locality 19 suggest that these rocks were deposited below wave base in a shelf or platform setting. The massive metalimestone contains some fossils tolerant of relatively restricted circulation (calcispheres, gastropods) as well as forms typical of settings with normal salinity (corals). The conodont fauna indicates a normal-marine, middle-shelf or shallower depositional setting.

At least 16 m of light-gray to pink to orange, locally dark-gray to black, well-bedded dolostone crops out at locality 18. These rocks consist of cyclic alternations of gray-weathering, mottled beds 40 to 180 cm thick, and orange-weathering, parallel-laminated beds 5 to 40 cm thick. Some gray beds contain vague cross laminae in 20- to 40-cm sets; the mottled texture in this lithology may reflect partial bioturbation. The orange beds contain some crinkly laminae as well as rip-up clasts, commonly laminated, as much as 4 cm long. Both gray and orange beds consist of a mosaic of euhedral to subhedral dolomite crystals, 20 to 400 μm in diameter, in which a ghostly relict texture of brownish peloids is preserved (fig. 10D). Peloids are rounded to ovoid and 40 to 200 μm in size; they may have formed as fecal pellets and (or) micritized skeletal grains. A few possible pelmatozoan fragments occur locally. Fenestral fabric is well developed in both lithologies; fenestrae range from elongate to irregular in shape and from less than 1 mm to 3 cm in size (fig. 10D). Most fenestrae are filled with clear calcite spar; some contain layers of micritic sediment and spar or are partly rimmed with solid hydrocarbons.

Sedimentary structures, particularly fenestral fabric, crinkly (algal?) laminae, and the abundance of peloids, suggest a shallow subtidal to intertidal setting for these rocks. A bed of mottled dolostone yielded only a few specimens of *Panderodus* sp. and *Belodella*? sp. (fig. 6, U and V) that suggest a Silurian or Devonian age no younger than earliest Frasnian (table 1).

More recrystallized rocks that may also have formed in relatively shallow water settings are exposed at localities 17 and 20. These rocks are very light gray- to tan-weathering, dark-gray, fine- to medium-crystalline metalimestone that forms massive cliffy outcrops 35 to 50 m high. Samples in which sedimentary texture is best preserved are bioclastic wackestones and packstones; some samples contain probable pelmatozoan fragments. These rocks lack features such as graded bedding, parallel and cross laminae, and lithic clasts observed in the deep-water facies described above. We suggest they formed in shallow-water shelf or platform settings. Recrystallized bioclastic wackestone at locality 20 was sampled for conodonts but none were found.

STRATIGRAPHY

Because some of the subunits and facies described above are undated or only broadly dated, the stratigraphy of the DOs unit in the study area is poorly constrained. We offer here our best interpretation of the data in hand to facilitate comparison with possibly correlative sequences elsewhere in the state.

Subunits A, B, and C are at least 15 m, 50 m, and 40 m thick, respectively, based on sections at localities 8, 11, and 16. If the alternations of more calcareous and more siliciclastic intervals at locality 15 are stratigraphic and not structural repeats, that section could be 300 to 400 m thick. Conodont data presented above permit the interpretation that subunits A, B, and C are all the same age, that is, late Early Silurian (Wenlockian). The conodont data also permit the interpretation that subunit B is slightly younger than subunit C. Conodont faunas from carbonate cobbles in the Upper Cretaceous sedimentary part of the Cantwell Formation, interpreted in Csejtey and others (1996) as derived from limestone turbidites of DOs, are of Silurian, Late Silurian, and Early Devonian age and provide an upper age limit for the deep-water part of DOs. At least part of the shallow-water facies is younger than any of the deep-water facies; strata at locality 19 are early Frasnian (earliest Late Devonian) in age.

One interpretation of the stratigraphy, based on available fossil data and geographic distribution of subunits, is that the DOs unit is generally older to the south and younger to the north. In this interpretation, subunit A, which is the most laterally extensive of the three subunits and is exposed chiefly in the southern part of the study area, is the oldest subunit. Subunits B and C, exposed chiefly in the western and central parts of the study area, respectively, are both

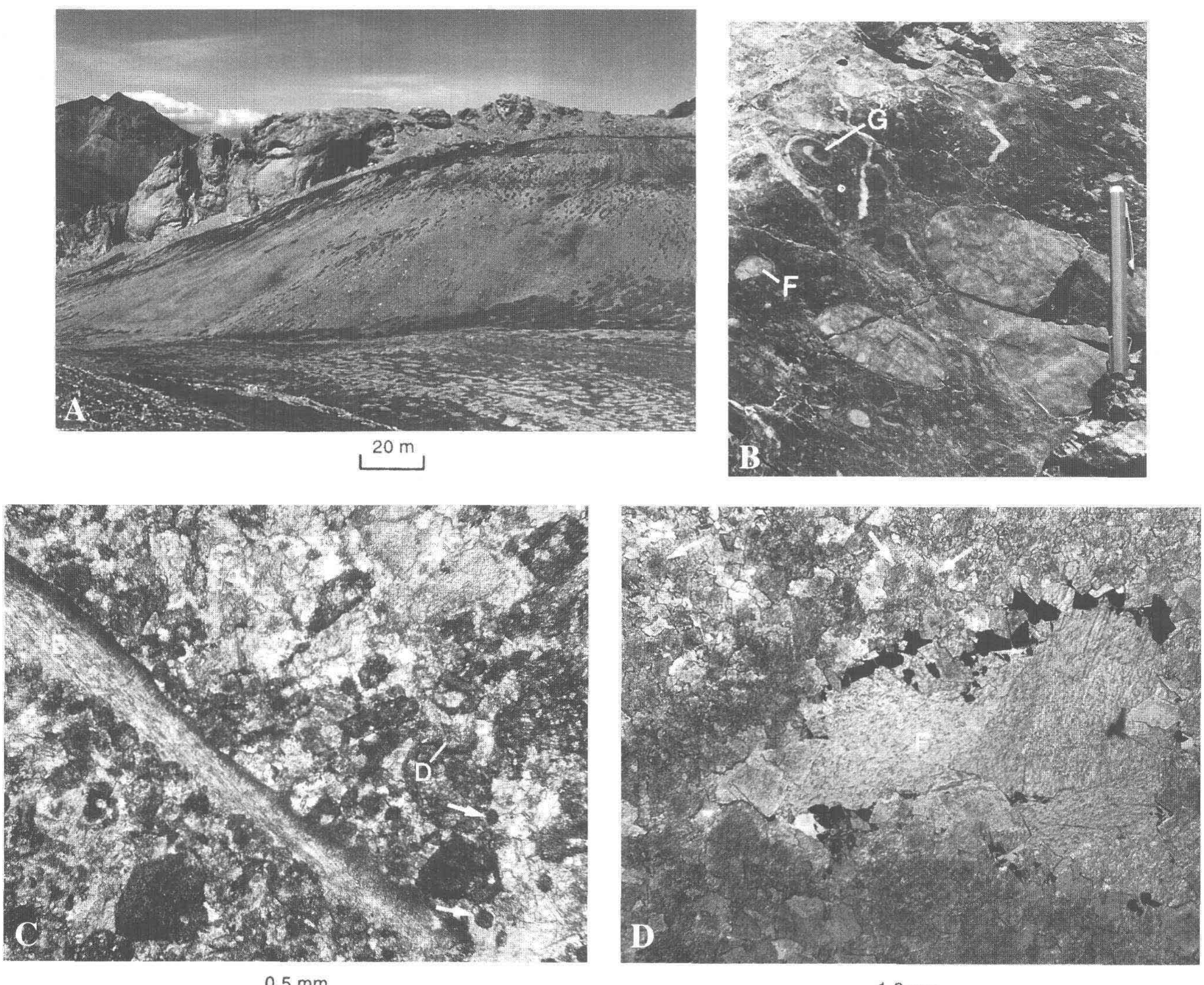


Figure 10. Sedimentary features of DOs shallow-water facies. A-C, Bioclastic-peloidal wackestone-packstone of early Frasnian age (fig. 2, loc. 19). Carbonate forms massive, light-colored layer above darker, recessive shale in A. Gastropods (G) and other fossil fragments (F) evident in outcrop in B. Photomicrograph (C) shows abundant peloids (indicated by arrows) and a brachiopod fragment (B) with dark micritic rim in partially dolomitized (D) matrix. D, Photomicrograph of mottled dolostone of Silurian or Devonian age with relict peloids (indicated by arrows); fenestrae (F) are partly rimmed with solid hydrocarbons and filled with clear calcite spar (fig. 2, loc. 18).

probably Silurian and could be younger than subunit A. Subunits B and C could be age equivalent but lithologically distinct facies with different provenances, which interfinger near the center of the study area (for instance, around locality 15). The nature of the contact between the deep-water strata which make up most of DOs and the youngest (Frasnian) strata exposed to the north is unclear—it could be an unconformity, perhaps structurally complicated, or a fault.

Mullen and Csejtey (1986) proposed the following stratigraphic succession for DOs: (1) 300 m of calcareous siliciclastic turbidites intercalated with limestone and shale; (2) 250 m of dark-gray to black, well-bedded lime mudstone to wackestone with rare argillite and chert interbeds; and (3) 20 m of massive to thick-bedded, partly dolomitic limestone of uniform age (Devonian), facies (shallow-water), and stratigraphic position (near the top of the unit) that can be traced along strike for at least 45 km. The thickness of the massive limestone was later given as 200 m (Csejtey and others, 1992) and then 40 to 70 m (Csejtey and others, 1996).

Our findings suggest at least three modifications to this stratigraphic succession. First, coarse-grained, thick-bedded to massive carbonate turbidites and debris flows like those described above in subunit C are an important part of DOs. Second, we could not confirm the presence of a thick interval of chiefly fine-grained carbonate overlying the calcareous siliciclastic turbidite interval. Third, massive limestone is an important part of the DOs unit, but it encompasses both deep-water facies of Silurian age (for example, locs. 14, 15) and shallow-water facies of Devonian age (loc. 19), as well as recrystallized, probably shallow-water metalimestone of uncertain age (locs. 17 and 20). Thus, although this massive limestone has been mapped as a single unit at 1:250,000 scale (for example, Csejtey and others, 1992), in detail it appears to consist of several cliff-forming limestone horizons whose relations with one another have not yet been determined.

STRUCTURE

Our reconnaissance studies of unit DOs reveal glimpses of a complex history of contractional deformation. Homoclinal sections were not recognized, and as noted above, piecing together a comprehensive stratigraphic section of the entire unit is not possible with our present knowledge. Nonetheless, certain broad tracts do appear to be dominated by a particular subunit. For example, sections containing abundant, relatively thick-bedded calcareous siliciclastic turbidites (subunit B) predominate in the area north of Red Mountain.

Within unit DOs, bedding typically strikes east and dips moderately to the south, although there is considerable variation in strike (fig. 11). The clustering of both upright and overturned bedding poles suggests the presence of north-vergent overturned folds. Such folds are well displayed in Lower Cretaceous and Upper Jurassic flysch in a mountainside a few kilometers north of locality 20. Evidence from outcrops and stereonets discloses two fold generations; only those folds that are demonstrably F2 are identified as such on the stereonets (fig. 11). Poles to fold axial surfaces delineate two clusters. One set dips moderately to the south; these folds would account for the main cluster of bedding poles. The other set of axial surfaces, which includes some known F2 folds, dips steeply to the northeast. Most fold hinges plunge fairly gently. F1 hinges trend west, whereas F2 hinges trend northwest. Cleavage (fig. 11) shows considerable scatter, but there is fair correspondence, at least, to the two main clusters of fold axial surfaces.

Rocks similar to DOs that are exposed in the McGrath and Lime Hills quadrangles (further discussed below) have broadly similar structural histories. In both areas, the early isoclinal folds verge northwest (Bundtzen and others, 1988, 1994). This deformation is presumably a consequence of Mesozoic convergence between the Wrangellia superterrane and interior Alaska.

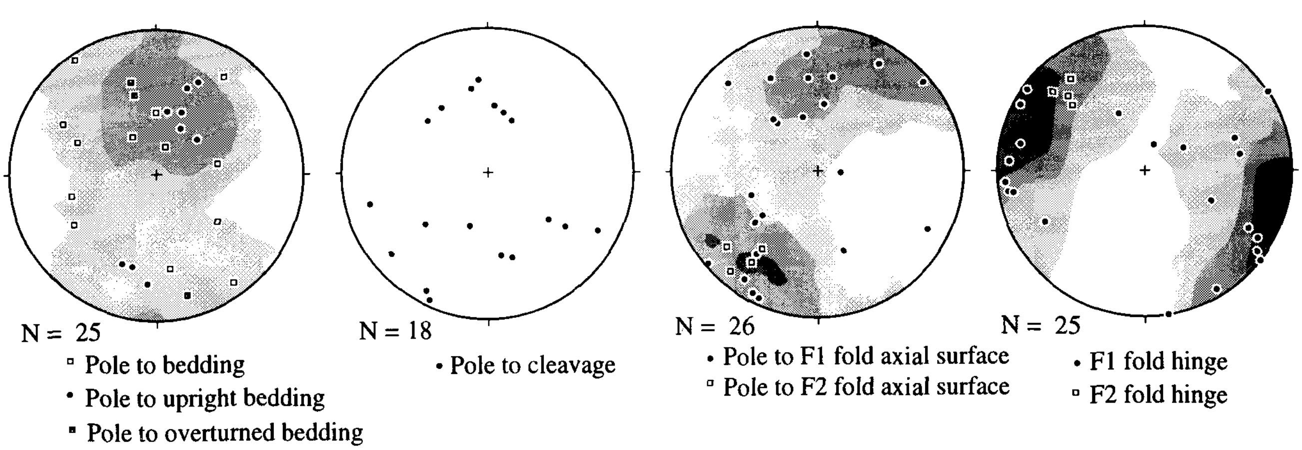


Figure 11. Lower hemisphere equal-area stereographic projections of structural data from unit DOs in Denali National Park. Contour interval is 2 sigma.

REGIONAL CORRELATION

Several aspects of the DOs unit in Denali National Park are distinctive and constrain correlations with coeval rocks (fig. 12). DOs consists chiefly of siliciclastic and calcereous turbidites, calcareous debris flows, and subordinate calcareous and siliceous hemipelagic deposits that accumulated in a slope and (or) basinal setting. The turbidites and debris flows are at least in part no older than Wenlockian (late Early Silurian) in age and have a mixed provenance including continental and subordinate volcanic sources. Deeper water strata are structurally (and stratigraphically?) overlain by shallower water carbonate facies at least in part of early Frasnian (earliest Late Devonian) age.

The DOs unit in the Denali area has been correlated with three sequences in central Alaska (fig. 1): (1) Rocks of the Dillinger terrane or sequence exposed to the southwest (for example, McGrath and Lime Hills quadrangles) (Jones and others, 1981, 1982, 1983); (2) rocks of the Mystic terrane or sequence exposed to the south (Talkeetna quadrangle) (Csejtey and others, 1996); and (3) rocks of the Nixon Fork terrane exposed to the west (for example, Medfra quadrangle) (Mullen and Csejtey, 1986; Csejtey and others, 1992). We consider these proposed correlations below.

In addition, we summarize below all other deep-water sequences of definite Silurian age known in Alaska, and compare their lithologies, faunas, specific depositional environments, and stratigraphic contexts to those of the DOs unit in the Denali area. Silurian deep-water sequences are known from east-central, eastern, southeastern, northern, and western Alaska; some of these sequences are overlain by Upper Devonian shallow-water carbonate rocks like those found in DOs.

CENTRAL ALASKA

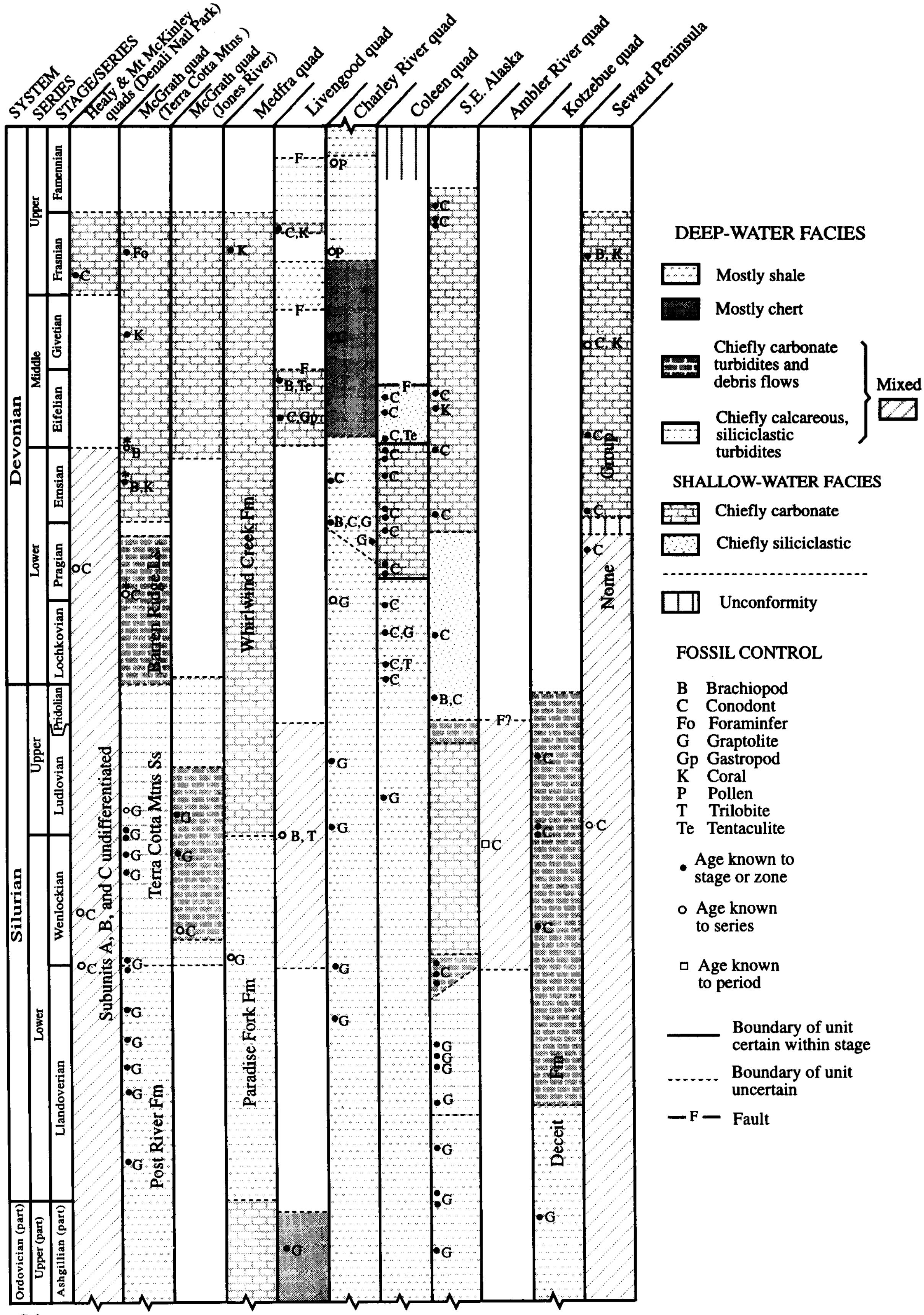
MCGRATH QUADRANGLE

The Dillinger terrane or sequence, which consists chiefly of lower Paleozoic deep-water rocks, has been studied at several localities in the McGrath quadrangle (Armstrong and others, 1977; Churkin and others, 1977; Bundtzen and Gilbert, 1983; Bundtzen and others, 1988, 1997; Churkin and Carter, 1996). It is also exposed to the southwest (Lime Hills and Sleetmute quadrangles) and northeast (west-central edge of the Talkeetna quadrangle; unit Pzd of Reed and Nelson, 1980).

In the Terra Cotta Mountains, in the southeastern part of the McGrath quadrangle (fig. 12, column 2), the section begins with at least 300 m of rhythmically layered, thin-bedded, laminated to cross-bedded silty limestone and shale (Lyman Hills Formation of Bundtzen and others, 1994; lower siltstone member of Post River Formation of Churkin and Carter, 1996). This unit has yielded Late Cambrian conodonts (Bundtzen and others, 1997) and earliest Ordovician (Tremadocian) graptolites (Churkin and Carter, 1996). It is overlain by about 395 m of hemipelagic graptolitic shale, siltstone, and ribbon chert (upper four members of Post River Formation of Churkin and Carter, 1996) that contain a very complete succession of Early Ordovician through early Early Silurian graptolites. This unit is overlain by at least 685 m of fine- to coarse-grained, calcareous and micaceous, quartzofeldspathic to subarkosic turbidites intercalated with finely laminated dark limestone (Terra Cotta Mountains Sandstone of Churkin and Carter, 1996). About 30 km north of the Terra Cotta Mountains, a distinctive lens within this turbidite unit contains altered ash layers and discrete volcanic lithic clasts (T.K. Bundtzen, Alaska Division of Geological & Geophysical Surveys, written commun., 1997; Bundtzen and others, 1997). The Terra Cotta Mountains Sandstone produces late Early and Late Silurian graptolites (Churkin and Carter, 1996; Bundtzen and others, 1997) and grades upward into more than 380 m of calcareous (locally dolomitic) turbidites with interbeds of channelized limestone conglomerate and slumped carbonate breccia (Barren Ridge Limestone of Churkin and Carter, 1996.) No fossils were found in the Barren Ridge Limestone in the Terra Cotta Mountains, but Blodgett and Gilbert (1992) obtained conodonts of Lochkovian to Pragian (Early Devonian) age from correlative beds in the northern Lime Hills quadrangle. The Dillinger sequence in the Terra Cotta Mountains is interpreted as having formed in a shallowing-upward succession of basinal, fan turbidite, and foreslope depositional environments (Gilbert and Bundtzen, 1984).

Limited paleocurrent data reported by Churkin and others (1977) first suggested that the Terra Cotta Mountains Sandstone was deposited by currents that flowed toward the northwest and northeast, whereas the Post River Formation and Barren Ridge Limestone were deposited by southwest- and west-flowing currents, respectively. More recently, Bundtzen and others (1988) reported additional paleocurrent data from the Terra Cotta Mountains Sandstone. All of the available data now indicate that the predominant paleocurrent direction for this unit appears to have been toward the northeast, with minor components of flow toward the northwest and south.

A succession somewhat similar to that in the Terra Cotta Mountains is described from the Jones River area along the east-central edge of the McGrath quadrangle (Armstrong and others, 1977). This section (figure 12, column 3), in ascending order, consists of 300 m of lithic arenite turbidites; 250 m of well-bedded dolomitic, argillaceous lime mudstone with worm burrows and trails and fine cross and parallel laminae, and at least 360 m of subgraywacke turbidites. Graptolites from the limestone unit are of late Wenlockian and early Ludlovian (latest Early and earliest Late Silurian) ages. Conodonts from three collections 84 to 126 m above the base of a similar limestone sequence about 15 km to the northeast are here considered late Llandoverian to Wenlockian in age


SYSTEM
SERIES
STAGE/SERIES
Healy & Mt McKinley quads (Denali Natl Park)
McGrath quad (Terra Cotta Mtns)
McGrath quad (Jones River)
Medfra quad
Livengood quad
Charley River quad
Coleen quad
S.E. Alaska
Ambler River quad
Kotzebue quad
Seward Peninsula
Devonian
Upper
Middle
Lower
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkovian
Silurian
Upper
Lower
Pridolian
Ludlovian
Wenlockian
Llandoverian
Ordovician (part)
Upper (part)
Ashgillian (part)
Subunits A, B, and C undifferentiated
Terra Cotta Mtns Ss
Post River Fm
Barren Ridge Ls
Whirlwind Creek Fm
Paradise Fork Fm
Nome Group
Deceit
Column
1
2
3
4
5
6
7
8
9
10
11
DEEP-WATER FACIES
Mostly shale
Mostly chert
Chiefly carbonate turbidites and debris flows
Chiefly calcareous, siliciclastic turbidites
Mixed
SHALLOW-WATER FACIES
Chiefly carbonate
Chiefly siliciclastic
Unconformity
FOSSIL CONTROL
B Brachiopod
C Conodont
Fo Foraminfer
G Graptolite
Gp Gastropod
K Coral
P Pollen
T Trilobite
Te Tentaculite
Age known to stage or zone
Age known to series
Age known to period
Boundary of unit certain within stage
Boundary of unit uncertain
F Fault

(fig. 6W-CC) and are virtually identical to some conodonts from unit DOs (table 1, loc. 14).

Deep-water strata in the McGrath and northern Lime Hills quadrangles are conformably or unconformably overlain (Gilbert and Bundtzen, 1984) by Lower (Emsian) to Upper Devonian, chiefly shallow-water, carbonate and subordinate siliciclastic rocks of the Mystic sequence (Bundtzen and Gilbert, 1983; Blodgett and Gilbert, 1992; Bundtzen and others, 1994). These rocks include a carbonate platform sequence of Frasnian age that crops out both north and south of the Farewell fault and contains locally abundant foraminifers with Siberian biogeographic affinities (Mamet and Plafker, 1982; Blodgett and Gilbert, 1992).

TALKEETNA QUADRANGLE

The Mystic terrane or sequence consists largely of units Pzus and Dl of Reed and Nelson (1980) in the northwestern Talkeetna quadrangle (not shown in fig. 12). Pzus is a "depositionally and structurally complex terrane of chiefly marine flyschoid sedimentary rocks" (Reed and Nelson, 1980, p. 7) that includes trench, slope, shelf, and terrestrial assemblages. The trench assemblage contains strata that are lithologically similar to deep-water parts of the DOs unit, but available fossil data suggest that they are mostly, perhaps completely, of Middle to Late Devonian and younger age. These lithologies include "terrigenous turbidites" (Reed and Nelson, 1980, p. 7), graywacke, and "wildflysch [that] locally contains house-sized blocks" of bedded limestone (Reed and Nelson, 1980, p. 8). No fossils of definitively Silurian or older age have been obtained from these deep-water rocks, but numerous collections of Devonian (including probable Middle and Late Devonian) age are reported by Reed and Nelson (1980) from limestones in Pzus. These limestones have chiefly shallow-water faunas; at least some appear to be blocks that were tectonically and (or) depositionally incorporated into coeval or younger deeper-water strata. Other parts of Pzus are definitely of post-Frasnian age; black shale and phosphatic chert contains Famennian (late Late Devonian) radiolarians, and some limestone layers are of Late Mississippian and Middle Pennsylvanian age (Reed and Nelson, 1980).

The Dl unit in the Talkeetna quadrangle provides a better match for the DOs unit, but only for the younger, shallow-water part of DOs. Dl consists of more than 95 m of intercalated thin-bedded micrite and massive, locally "reefoid" biostromal beds of colonial rugose corals, stromatoporoids, and bryozoans; it is interpreted as a series of small patch reefs and interreef beds (Reed and Nelson, 1980). Some parts of Dl may be of Early and (or) Middle Devonian age (Reed and Nelson, 1980), but much of the unit appears to be Late Devonian. Seven localities in Dl yielded megafossils of Frasnian or probable Frasnian age; brown to black shales with thin limestone interbeds near the top of the Dl unit contain conodonts of late Frasnian age (Reed and Nelson, 1980). Frasnian fossil assemblages in both DOs and Dl contain some of the same genera and species of atrypid and spiriferid brachiopods (Csejtey and others, 1996).

MEDFRA QUADRANGLE

The Nixon Fork terrane includes abundant lower Paleozoic rocks; it is widely exposed and particularly well-studied in the Medfra quadrangle (Dutro and Patton, 1982) but also crops out to the northeast, south, and southwest (fig. 1). In the Medfra quadrangle, a thick Ordovician through Devonian, largely platform carbonate sequence is punctuated by an incursion of Silurian deeper water facies (fig. 12, column 4). This facies, named Paradise Fork Formation by Dutro and Patton (1982), consists of at least 1,000 m of dark-

◀**Figure 12.** Correlation, lithologies, fossil control, and depositional environments of uppermost Ordovician through Devonian rocks in selected areas of Alaska. See figure 1 for location of columns. Only fossils that most restrict age of collection or unit are listed; fossils listed alphabetically. Conodont collection of Early Devonian age in column 1 is from a cobble in Upper Cretaceous part of Cantwell Formation interpreted (Csejtey and others, 1996) as derived from DOs. Asterisk above some fossil symbols in column 2 indicates that these collections are from strata in northern part of Lime Hills quadrangle that are considered correlative (see for example, Bundtzen and others, 1994) with rocks in Terra Cotta Mountains. Silurian section in Black River quadrangle (not shown here but discussed in text) is identical to that from Coleen quadrangle shown in column 7; Devonian sections in the two areas are slightly different. Column 10 represents Deceit Formation, considered part of Nome Group by Till and Dumoulin (1994) and exposed only in the Kotzebue quadrangle; column 11 represents the Nome Group (part) exclusive of the Deceit Formation, exposed in the Kotzebue quadrangle and elsewhere on Seward Peninsula. Terranes represented as follows (Silberling and others, 1994): columns 1-3, Dillinger (Devonian and older deep-water facies) and Mystic (Devonian shallow-water facies); column 4, Nixon Fork; column 5, Livengood; column 6, ancestral North America; column 7, Porcupine; column 8, Alexander; column 9, Hammond subterrane of Arctic Alaska; columns 10 and 11, Seward. Data sources as follows: column 1, this paper, Csejtey and others (1996); column 2, Mamet and Plafker (1982), Bundtzen and Gilbert (1983), Blodgett and Gilbert (1992); Bundtzen and others (1994), Churkin and Carter (1996); column 3, Armstrong and others (1977), this paper; column 4, Dutro and Patton (1982); column 5, Blodgett and others (1988), Weber and others (1994); column 6, Churkin and Brabb (1965); column 7, Churkin and Brabb (1967); column 8, Churkin and Carter (1970), Savage (1977, 1985, 1992), Eberlein and others (1983), Soja (in press), A.G. Harris, unpub. data (1979, 1985); column 9, Dumoulin and Harris (1988); columns 10 and 11, Till and others (1986), Ryherd and Paris (1987), Till and Dumoulin (1994), A.G. Harris, unpub. data. A.G. Harris and Claire Carter revised the age of graptolite and conodont faunas in some of references listed above.

gray, thin-bedded, platy, silty limestone and black shale; limestone bodies and lenses as much as 5 m thick are found in the upper part of the unit. Graptolites from the lower part of the unit are latest Llandoverian to early Wenlockian; the uppermost beds are probably no younger than Wenlockian (Dutro and Patton, 1982). The unit is overlain by Upper Silurian through Devonian, predominantly shallow-water carbonate rocks of the Whirlwind Creek Formation; the upper part of this unit contains Frasnian (early Late Devonian) corals (Dutro and Patton, 1982).

Deeper water facies of Paleozoic age also crop out southeast of the Nixon Fork terrane in the Medfra quadrangle. These rocks, the East Fork Hills Formation of Dutro and Patton (1982), make up the East Fork subterrane (Patton and others, 1994) of the Minchumina terrane (Jones and others, 1981; Silberling and others, 1994) (fig. 1). (Decker and others, 1994, include the Minchumina terrane in the White Mountain sequence of the Farewell terrane.) The East Fork Hills Formation is poorly exposed and consists chiefly of thin-bedded limestone and dolostone and subordinate chert and siliceous siltstone. The formation has been assigned an Early Ordovician through Middle Devonian age on the basis of scattered, largely long-ranging conodont collections; definitively Silurian fossils have not been reported (Dutro and Patton, 1982; Patton and others, 1994).

SUMMARY

Jones and others (1981, 1982, 1983) included the DOs unit of Csejtey and others (1992) in their Dillinger terrane, correlating it with deep-water strata exposed in the northwestern Talkeetna and eastern McGrath quadrangles and adjacent areas to the southwest. Our data support this correlation and also suggest specific correlations between the subunits we recognize in DOs and the formations recognized by Churkin and Carter (1996) and Bundtzen and others (1994) in the McGrath and northern Lime Hills quadrangles.

Fine-grained, thin-bedded calcareous and siliceous strata of our subunit A are lithologically most like the Upper Cambrian to Lower Ordovician Lyman Hills Formation of Bundtzen and others (1994) (T.K. Bundtzen, written commun., 1997). Subunit A also has similarities with some members of the overlying Ordovician to lower Lower Silurian Post River Formation of Churkin and Carter (1996) but lacks the abundant graptolites characteristic of that unit. Graptolites could be present in parts of subunit A that were not examined during our reconnaissance investigations or could have been obscured by metamorphism and (or) structural complexities. Correlation with the Lyman Hills Formation and (or) the Post River Formation suggests an age of early Early Silurian or older for subunit A.

Upper Lower Silurian (Wenlockian or younger) siliciclastic turbidites of subunit B are similar in age and lithology to the Terra Cotta Mountains Sandstone of Churkin and Carter (1996) in the McGrath quadrangle. Both units contain carbonate interbeds, calcareous siliciclastic turbidites of mixed provenance, and subordinate volcanogenic components. The paleocurrent data we obtained from subunit B of DOs (flow to the south) differ from those reported by Churkin and others (1977) and Bundtzen and others (1988) from turbidites in the Terra Cotta Mountains (flow dominantly to the northeast), but the significance of this difference is unclear. It could be paleogeographically meaningful, but it could also reflect technical and (or) post-depositional complications such as small data sets, errors introduced during retrodeformation, and (or) large-scale structural rotations.

Thin-bedded to massive calcareous turbidites and debris flows of subunit C resemble the Barren Ridge Limestone of Churkin and Carter (1996), particularly as described by Bundtzen and others (1988, 1994) in the eastern McGrath and northern Lime Hills quadrangle. The Barren Ridge Limestone is considered Late Silurian (Ludlovian) or younger, however, whereas subunit C has produced late Early Silurian (Wenlockian) conodonts. As discussed above, lithologic and faunal evidence suggests that the conodonts recovered from subunit C reflect the depositional age of the subunit and were not reworked from significantly older beds. If so, subunit C may represent a coarser grained equivalent of the limy intervals recognized in the Terra Cotta Mountains Sandstone, rather than a correlative of the Barren Ridge Limestone.

The Frasnian part of the Mystic sequence platform carbonate rocks that overlie the Dillinger sequence in the McGrath quadrangle correlates well with the shallower water, Frasnian part of DOs.

Csejtey and others (1996) suggested that the DOs unit could be correlated with at least parts of units Pzus and Dl of Reed and Nelson (1980). However, there is no paleontological evidence that the Pzus unit contains any deep-water strata as old as Silurian; indeed, fossil collections reported by Reed and Nelson (1980) indicate that most, perhaps all of these rocks are Middle Devonian or younger. The Frasnian part of Dl is a good lithologic and paleontological match for the Frasnian part of DOs.

Mullen and Csejtey (1986) and Csejtey and others (1992) concluded that the DOs unit is a tectonically fragmented piece of the Nixon Fork continental margin that includes most or all of the deep-water segment, and part of the shallow-water segment, of the Nixon Fork terrane. However, although the deep-water segment of the Nixon Fork terrane (the Paradise Fork Formation of Dutro and Patton, 1982) is at least in part coeval with the deep-water part of the DOs unit, the Paradise Fork is more fine grained than DOs and lacks siliciclastic turbidites. The Frasnian part of the Whirlwind Creek Formation (part of the shallow-water segment of the Nixon Fork terrane) is correlative with the Frasnian part of DOs. Deep-water strata southeast of the Nixon Fork terrane in the Medfra quadrangle (the East Fork Hills Formation of Dutro and Patton, 1982) may correlate, at least in part, with DOs, but they are finer grained and lack a significant siliciclastic component.

EAST-CENTRAL ALASKA

Deep-water Silurian strata crop out in the northwestern part of the Livengood quadrangle (fig. 1; fig. 12, column 5), in the Livengood stratigraphic belt (Dover, 1994) or Livengood terrane (Silberling and others, 1994). The Livengood belt has been interpreted as part of the North American continental margin (Selwyn Basin sequence) offset by strike-slip faulting along the Tintina fault (Dover, 1994). Other workers (for example, Grantz and others, 1991) have suggested that strata of the Livengood belt were deposited on Cambrian oceanic crust and may be of non-North American origin.

The Lost Creek unit (Blodgett and others, 1988) in the Livengood belt is a chiefly siliciclastic basinal succession about 50 m thick (R.B. Blodgett, oral commun., 1992) that includes a 15-m-thick carbonate limestone lens interpreted by Blodgett and others (1988) as a debris flow derived from a shallow-marine carbonate platform. The limestone includes brachiopods, crinoid columnals, ostracodes, trilobites, rugose corals, and possible calcareous algae; the brachiopods and trilobites indicate a Wenlockian to Ludlovian age (Blodgett and others, 1988). The Lost Creek unit overlies the Livengood Dome chert, a chiefly basinal succession that contains Late Ordovician (Ashgillian) graptolites, and is in turn overlain by a structurally complex and poorly exposed succession of Middle and Upper Devonian, chiefly shallow-marine siliciclastic and calcareous units (Weber and others, 1994). A discontinuous limestone, thought by Weber and others (1994) to represent a series of biogenic buildups at the base of their Quail unit, contains conodonts and corals that restrict its age to the late Frasnian.

The Lost Creek unit is similar in age and lithology to the deep-water part of DOs but is apparently thinner. Siliciclastic turbidites in the Lost Creek unit have not been described in sufficient detail to allow a precise correlation with those in DOs. The Frasnian limestone in the Quail unit is broadly correlative with the Frasnian part of DOs, although DOs may be slightly older.

EASTERN ALASKA AND ADJACENT PARTS OF CANADA

Basinal facies of Silurian age crop out discontinuously throughout eastern Alaska and adjacent Canada, particularly in the Charley River, Black River, and Coleen quadrangles (fig. 1; fig. 12, columns 6 and 7). In the Charley River quadrangle, these rocks are considered part of ancestral North America by Silberling and others (1994) but have been assigned to the Tatonduk terrane by some workers (for example, Howell and others, 1992). Correlative rocks in the Black River and Coleen quadrangles are generally called the Porcupine terrane (for example, Silberling and others, 1994). Most workers, even those who believe that rocks in eastern Alaska represent distinct terranes, infer that these terranes formed as part of the North American continental margin.

Throughout eastern Alaska and adjacent Canada, Silurian deep-water facies are assigned to the Road River Formation (Group in Canada) of Ordovician through Early Devonian age and consist chiefly of shale, with local thin beds of chert, dolostone, and limestone (Churkin and Brabb, 1965). The Silurian section is as much as 150 m thick in the Charley River quadrangle, but less than 10 m thick in the Black River and Coleen quadrangles (Churkin and Brabb, 1965, 1967). Upper Devonian rocks consist chiefly of siliciclastic turbidites of the Nation River Formation in the Charley River quadrangle (Churkin and Brabb, 1965) and have not been reported to the north (Black River and Coleen quadrangles).

Silurian deep-water facies in eastern Alaska thus are finer grained than those of DOs; siliciclastic sandstone turbidites are rare or absent. No rocks lithologically and biostratigraphically correlative with the Frasnian shallow-water carbonate part of DOs have been reported from this area.

Rocks of the Dillinger terrane or sequence in the McGrath and Lime Hills quadrangles have been correlated with Paleozoic rocks in the Selwyn Basin (Yukon and Northwest Territories, Canada) by previous workers. Bundtzen and Gilbert (1983) and Bundtzen and others (1988, 1994), for example, have correlated the Lyman Hills and Post River Formations with the Rabbitkettle Formation and Road River Group, respectively, of the Selwyn Basin. Like eastern Alaska, the Selwyn Basin lacks siliciclastic sandstone turbidites of Silurian age. However, the Sapper Formation (Gordey and Anderson, 1993), a sequence of several hundred meters of Silurian and Devonian limestone and silty limestone that is found in parts of the Selwyn Basin, could represent a distal equivalent of the proximal fan deposits of the Terra Cotta Mountains Sandstone (T.K. Bundtzen, written commun., 1997). Platform carbonate rocks of Frasnian age have not been reported from the Selwyn Basin or adjacent shelf successions; as in eastern Alaska, upper Devonian rocks in the Yukon are chiefly siliciclastic turbidites (Gordey and Anderson, 1993).

SOUTHEASTERN ALASKA

Silurian deep-water strata are an important part of the Alexander terrane (Silberling and others, 1994) in southeastern Alaska (fig. 1; fig. 12, column 8). The Alexander terrane is generally interpreted as a displaced fragment of an early through middle Paleozoic island arc, but the original position of this arc is controversial. Recent work suggests a position close to northern North America (Bazard and others, 1995).

The Silurian section in the Alexander terrane is summarized by Soja (in press). In the southern part of the terrane, the section begins with the deep-marine Descon Formation, about 3,000 m of Middle Ordovician through Lower Silurian volcanic rocks (including flows, breccias, tuffs, and agglomerates), graywackes, quartzofeldspathic arenites, mudstones, cherts, shales, and minor limestones. Upper Llandoverian carbonate turbidites and Ludlovian-Pridolian(?) turbidites and calcareous debris flows are found at the base and near the top of the overlying unit, the Heceta Formation, which is more than 3,000 m thick; shallow-water carbonate platform strata, however, make up most of the Heceta. The Heceta is overlain by the Karheen Formation, 1,800 m of Upper Silurian and (or) Lower Devonian terrigenous red beds and shallow-marine deposits. Deep-water strata may be somewhat younger in the northern part of the Alexander terrane; the Bay of Pillars Formation (middle Llandoverian-early Ludlovian) and Point Augusta Formation (Upper? Silurian), both interpreted as deep-marine deposits, contain abundant graywackes, subordinate limestones, and volcanic rocks. Volcanic lithic fragments are the most abundant clasts in samples point-counted from the Bay of Pillars and Point Augusta Formations (Karl and Giffen, 1992).

Devonian strata in the Alexander terrane consist primarily of shallow-marine carbonate rocks, siliciclastic strata, and (in the Middle and Upper Devonian) subordinate mafic-intermediate volcanic rocks (Gehrels and Berg, 1994). Megafossils and conodonts of Frasnian and Famennian age have been identified from the Wadleigh Limestone (Eberlein and others, 1983; Savage, 1992; A.G. Harris, unpub. data, 1985).

Deep-water Silurian strata in southeast Alaska have some similarities with the Silurian part of DOs. In particular, both sequences contain calcareous and siliciclastic turbidites as well as calcareous debris flows. However, Silurian turbidites in the Alexander terrane, particularly in the southern part of the terrane, are partly older (pre-Wenlockian) than those in DOs, which are at least in part Wenlockian and younger. Turbidites in the northern part of the Alexander terrane may correlate better with those in DOs, but age control in these northern units is poor (Karl and Giffen, 1992). Composition distinguishes all Silurian deep-water deposits in the Alexander terrane from Silurian strata in DOs, however. Throughout southeastern Alaska, volcanic rocks are a much larger part of the Silurian deep-water section, and volcanic lithic clasts are a correspondingly larger component of Silurian turbidites. The upper Frasnian and lowermost Famennian parts of the upper Wadleigh Limestone appear to be younger than the Frasnian part of DOs.

NORTHERN ALASKA

Deep-water Silurian metasedimentary rocks are exposed in the northeast Ambler River quadrangle in the western Brooks Range (fig. 1; fig. 12, column 9). These unnamed rocks are part of the Hammond subterrane of the Arctic Alaska terrane (Silberling and others, 1994). The Hammond subterrane has been interpreted as a composite of fragments displaced from the North American(?) and (or) Siberian(?) continental margins (Nokleberg and others, 1994).

Deep-water Silurian strata in the northeast Ambler River quadrangle consist of at least 200 m of intercalated fine- to coarse-grained siliciclastic and calcareous turbidites and contain late Early to Late Silurian (Wenlockian to Ludlovian) conodonts (Dumoulin and Harris, 1988) that are virtually identical to some conodonts in unit DOs (table 1, loc. 14). The turbidites overlie metacarbonate rocks of unknown age and underlie quartz metaconglomerate of Mississippian(?) age; the latter contact has been interpreted as an unconformity (Mayfield and Tailleur, 1978) but may be a fault. Siliciclastic turbidites in this unit consist chiefly of calcareous grains (as much as 30%), quartz (as much as 30%), and sedimentary lithic grains (5-10%), as well as lesser amounts of feldspar, volcanic lithic clasts, and chert (locally containing radiolarians). Dolomitic limestone turbidites form 10 to 20 percent of this unit and increase in abundance upward. Some beds contain clasts as large as 10 cm; many beds contain fossil fragments, including corals, gastropods, bryozoans, brachiopods, conularids, and orthocone cephalopods. This unit has been recognized in a small area near Kavachurak Creek, but lithologically similar strata that are at least in part stratigraphically correlative have been recognized throughout the Ambler River quadrangle (Dumoulin and Harris, 1988).

Deep-water Silurian strata in the Ambler River quadrangle are similar in age and lithology to the deep-water part of DOs. But Frasnian shallow-water carbonate rocks that could provide a match for the younger part of DOs have not been reported from this area.

WESTERN ALASKA

Lower Paleozoic rocks lithologically and stratigraphically correlative with DOs are found on the northern and southeastern Seward Peninsula (fig. 1); all are part of the Seward terrane (Silberling and others, 1994) and are included in the Nome Group by Till and Dumoulin (1994) (map units DObm, D€ks, and D€bm of Till and others, 1986)[3]. These rocks retain locally well-preserved sedimentary features but have been metamorphosed to blueschist, greenschist, and locally amphibolite facies. The Seward terrane has been interpreted as a metamorphosed and deformed fragment displaced from the North American continental margin (Nokleberg and others, 1994).

[3] DObm, Ordovician through Devonian black metalimestone and marble; D€ks, Cambrian through Devonian calcschist; D€bm, Cambrian through Devonian black marble.

In the north (southern part of the Kotzebue quadrangle; fig. 1; fig. 12, column 10), a fault-bounded interval about 300 m thick has been called the Deceit Formation and divided into three members by Ryherd and Paris (1987). These strata are less ductilely deformed than, but are thermally equivalent to, surrounding parts of unit DObm (J.A. Dumoulin and A.G. Harris, unpub. data, 1995) and are included in the Nome Group by Till and Dumoulin (1994). The lowest member is chiefly pelagic and hemipelagic deposits and contains graptolites of Middle and Late Ordovician age (Ryherd and others, 1995); the upper members consist of carbonate turbidites and debris flows deposited as a prograding base-of-slope apron (Ryherd and Paris, 1987). The middle member contains conodonts of Wenlockian and early to middle Ludlovian age (A.G. Harris, unpub. data, 1987); the upper member has not been dated but is considered of probable Late Silurian (and younger?) age (Ryherd and Paris, 1987). The coarsest beds in this formation are breccias at least 15 to 20 m thick that contain clasts as much as 5 m in diameter (Dumoulin and Till, 1985). Turbidites and debris flows in the Deceit Formation contain little siliciclastic material, but calcareous turbidites in adjacent and correlative strata of the DObm and D€ks units (Till and others, 1986) contain locally abundant quartz, albite, chlorite, white mica, and graphite.

The Nome Group on the southeastern Seward Peninsula (unit D€bm of Till and others, 1986) includes metamophosed, pure and impure turbidites similar to those described above, although coarse-grained carbonate debris flows are rare or absent in these rocks (fig. 12, column 11). Conodonts of late Early to Late Silurian (Wenlockian to Ludlovian) and middle Early Devonian (Pragian) age were obtained from this unit.

Across Seward Peninsula, Devonian shallow-water metacarbonate rocks of the Nome Group (map unit Ddm of Till and others, 1986)[3] appear to have been unconformably deposited on older, deeper water Nome Group rocks (Till and Dumoulin, 1994). These shallow-water strata contain conodonts and (or) megafossils of late Early (Emsian), Middle, and early Late Devonian (Frasnian) age (Till and others, 1986).

DISCUSSION

As noted above, the DOs unit in the Denali area correlates well with parts of the Farewell terrane exposed in central Alaska. But sedimentologic and biostratigraphic similarities also exist between DOs and rocks elsewhere in Alaska that have been included by previous workers in six other tectonostratigraphic terranes. A full discussion of the paleogeographic and tectonic histories of Alaskan terranes is beyond the scope of this paper, but our comparisons of Silurian deep-water strata throughout the state provide several useful constraints for terrane analysis. Of particular interest are the distribution patterns of calcareous siliciclastic turbidites of Silurian (Wenlockian to Ludlovian) age and the presence of a volcanic component in (and intercalated with) these turbidites.

Lower Paleozoic rocks in the Farewell terrane have previously been correlated with coeval strata in the Selwyn Basin of western Canada (Bundtzen and Gilbert, 1983; Bundtzen and others, 1988, 1994), as have rocks of the Livengood, Porcupine, and Tatonduk terranes (Dover, 1994). These correlations imply that all of these sequences formed in relative proximity to each other along the North American continental margin. Our analyses suggest that if this interpretation is valid, these terranes record a gradient in Silurian turbidite deposition. Accumulations of calcareous siliciclastic sandstone are thickest (>500 m) in the Farewell terrane (Terra Cotta Mountains Sandstone), notably thinner (50 m) in the Livengood terrane (Lost Creek unit), and apparently absent in the Porcupine and Tatonduk terranes (Road River Formation).

Thick (200-300 m) turbidite successions of Silurian age are also found in terranes of possible North American affinity in northern and western Alaska. The similarity in age and composition of turbidite successions in the Hammond subterrane (unnamed rocks in the Ambler River quadrangle) and in the Seward terrane (parts of the Nome Group) to those of the Farewell terrane (Terra Cotta Mountains Sandstone) suggest that all three successions were derived from a common source and were deposited along the same continental margin. Thus, if a North American origin is accepted for the Farewell terrane, Silurian stratigraphic correlations support a North American origin for both the Seward terrane and the Hammond subterrane as well, and imply Silurian proximity between all three terranes.

A third implication of our stratigraphic comparisons is that volcanic material preserved in the DOs unit, the Terra Cotta Mountains Sandstone, and other Silurian turbidite sequences could have been derived from the island arc represented by the Alexander terrane. Volcanic rocks of Silurian age are recognized in the Alexander terrane (Churkin and Carter, 1970; Eberlein and others, 1983; Gehrels and Berg, 1994) but have not been reported from elsewhere in Alaska or adjacent parts of Canada. A position close to northern North America during Silurian and Early Devonian time has been proposed for the Alexander terrane based on paleomagnetic, detrital zircon, and paleontologic observations (Bazard and others, 1995). Faunal similarities suggest close paleogeographic ties between the Farewell and Alexander terranes during the Silurian (Bazard and others, 1995; Soja, in press). Careful analyses of the precise age and composition of volcanic components in these terranes could strengthen this interpretation.

[4] Ddm, Devonian dolostone, metalimestone, and marble.

CONCLUSIONS

The DOs unit in the Denali National Park area is a chiefly deep-water sequence, at least in part of Silurian age, of calcareous and siliciclastic turbidites, calcareous debris flows, and calcareous and siliceous hemipelagic deposits. The unit also contains shallow-water facies that are at least in part of Late Devonian (early Frasnian) age. DOs correlates best with rocks of the Dillinger sequence and the lower part of the Mystic sequence (Farewell terrane) exposed to the southwest in the eastern McGrath quadrangle. Intriguing sedimentologic and biostratigraphic similarities also exist with rocks of east-central Alaska (Livengood terrane) and western Alaska (Seward terrane). Less compelling correlations can be made between rocks in southeastern Alaska (Alexander terrane) and northern Alaska (Hammond subterrane of Arctic Alaska terrane). Rocks in easternmost Alaska (Porcupine and Tatonduk terranes) correlate least well because they lack the thick interval of calcareous siliciclastic turbidites that is characteristic of DOs.

Depositional patterns and composition of Silurian turbidites in terranes throughout Alaska provide constraints on the ultimate origin of these terranes. Previous studies have suggested that all Alaskan terranes which include Silurian deep-water strata could have originated along or adjacent to the North American continental margin. Our correlations yield some support for this interpretation but imply an uneven distribution of Silurian turbidites along this margin. The Alexander terrane contains the only volcanic rocks of Silurian age reported from Alaska or western Canada and could have provided a source for the volcanic material in DOs and related rocks.

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